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ROYAL METEOROLOGICAL SOCIETY

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CONTENTS

PAGE

P. A. SHEPPARD—Presidential Address—Education and research in meteorology in the United Kingdom 187

H. WEXLER—Seasonal and other temperature changes in the Antarctic atmosphere .. 196

G. B. TUCKER—Mean meridional circulation in the atmosphere 209

J. I. P. JONES and F. PASQUILL—An experimental system for directly recording statistics of the intensity of atmospheric turbulence 225

C. J. ADKINS—The small ion concentration and space charge near the ground .. 237

H. C. PEREIRA—Practical field instruments of radiation and of evaporation 253

J. R. ROSSITER—Research on methods of forecasting storm surges on the east and south coasts of Gt. Britain 262

G. GHANGOPADHYAYA and H. RIEHL—Exchange of heat, moisture and momentum between *Hurricane Ella* (1958) and its environment 278

Shorter Contributions—

B. N. CHARLES—Utility of vector stretch correlation coefficients 287

L. K. SINHA—Method of determining the constant in the balloon-ascent formula .. 291

Discussions—

F. A. BERSON—Some measurements on undercutting cold air (*Q.J.*, **84**, p. 1) 294

J. S. SAWYER—Temperature, humidity and cloud near fronts in the middle and upper troposphere (*Q.J.*, **84**, p. 375) 295

F. K. BALL—Long waves, lee waves and gravity waves (*Q.J.*, **85**, p. 24) 297

B. J. MASON and J. MAYBANK—Ice-nucleating properties of some natural mineral dusts (*Q.J.*, **84**, p. 235) 298

H. H. LAMB—The southern westerlies: a preliminary survey; main characteristics and apparent associations (*Q.J.*, **85**, p. 1) 299

Report of the Council for 1958 302

Proceedings at meetings of the Society 314

Award of second Napier Shaw Memorial Prize 317

Reviews—

Descriptive meteorology, H. C. Willett and F. Sanders (C.J.B.); *Météorologie générale*, Tome II, J. Roulleau and R. Trochon (H.L.W.); *Weather and climate*, C. E. Koeppe and G. C. De Long (G.M.H.); *Klimatographie von Österreich*, Pt. I (Eds.) F. Steinhauser, O. Eckel and F. Lauscher (G.A.B.); *The weather-conditioned house*, G. Conklin (R.E.L.); *The magneto-ionic theory and its applications to the ionosphere*, J. A. Ratcliffe (T.G.C.); *Physics of meteor flight in the atmosphere*, E. J. Opik (R.J.M.); *Interscience tracts on physics and astronomy*, No. 6 (Ed.) R. E. Marshak (R.J.M.) 318

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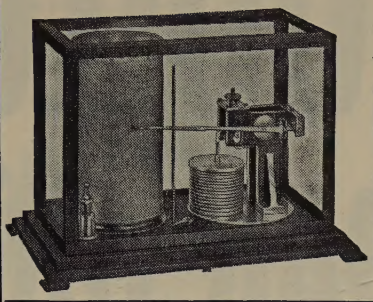

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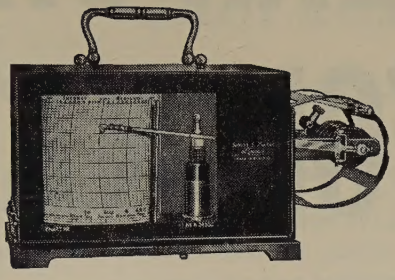

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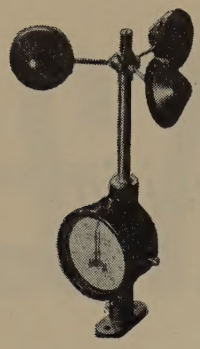

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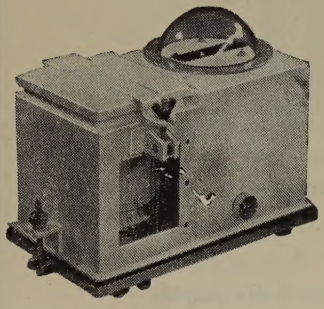

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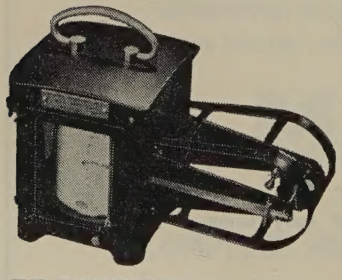

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Education and research in meteorology in the United Kingdom

By P. A. SHEPPARD

Presidential Address delivered before the Royal Meteorological Society on 22 April 1959

1. Introduction

In his second Presidential Address, in 1882, G. J. Symons, F.R.S., said : "I . . . propose devoting my time to that which I believe to be most necessary, viz. the consideration of the present state and future prospects of meteorology. I know that this subject has been treated of by many of my predecessors but it can hardly be too often brought before us, and it presents itself differently to every mind. In fact, as every President has to give two addresses, it might be well to make it an unwritten law that the second address of every President should express his views on the present state and future prospects of meteorology."

Few Presidents since Symons have accepted his advice, but my immediate predecessor, Dr. R. C. Sutcliffe, F.R.S., was, wittingly or unwittingly, one of them when he addressed us on ' An outlook on meteorology and the Society.' My title is less comprehensive but one can hardly discuss education and research in meteorology without an eye to the subject as a whole. I have selected it because I sense that the present are rather critical days for meteorology and that we should have regard to our responsibility for shaping its future. The post-war surge of activity in the broad but conventional aspects of the subject shows signs of expending itself, not however because the basic problems posed have been solved, whereas quite new fields of endeavour, with rockets and satellites, are being opened up. It is in the nature of a science to burst out, every now and again, into new fields, particularly as new techniques present themselves, and there should be no hindrance from scientists to this process. But we should try to see broadly where we wish to go and let our views be known to those who influence our future. *Laissez-faire* is no more operative today in science than in other human affairs.

It is somewhat regrettable that I think it necessary to say first what I take the word meteorology to imply. For me it is the study of the physical and chemical state of the *whole* atmosphere and of its evolution*. This is more than the term is sometimes taken to connote, the application of meteorology to weather forecasting having limited its scope in some minds to ' weather science.' It is not however possible, even to earth-bound mortals, to say where atmospheric behaviour ceases to influence their weather, and man – still less dog – is far from earthbound today. Moreover, science, although influenced by human activities, does not accept limitations imposed by immediate applications. Scientific sense is made rather by meteorology embracing all those aspects of atmospheric behaviour which have a substantial amount in common, whatever the applicability or lack of it. I do not know where the atmosphere ceases to behave as a compressible fluid under gravity, with motions energized directly or indirectly by the sun. It is true that some branches of the subject, for example ionospheric physics, have become so specialized in subject matter and technique as largely to have isolated themselves from the rest. But the isolation, while understandable, carries penalties and this Society should do what it can to maintain communication. It is scientific economy to ensure, as far as we may, that the understanding acquired for the behaviour of one part of the atmosphere shall not be overlooked when studying another part. But I am anticipating.

* I take this definition to include climatology – a study of state and its evolution over the larger time-scales.

Because there are those who study some parts of meteorology without identifying themselves with it (though the distinction of their subject matter is generally less than for ionospheric physics), my use of the word meteorology may give rise to some misinterpretation. I hope, however, that the context will clarify.

It will be my thesis that meteorology as a whole must make a bigger impact on our universities if it is to advance as we see it capable and worthy of doing. This is a problem both in education and research, and I shall deal first with the former, realising that there is no obvious first. Before dealing with either it is appropriate to review briefly the demands of society for the meteorologist.

2. The demand for meteorology by society

The demand for meteorologists in the United Kingdom comes almost entirely from the state meteorological services (Meteorological Offices, Colonial Services, Naval Weather Service). Thus, the Meteorological Office, London, has over the past decade or so required to recruit annually about five research officers (Scientific Officer class) and twenty technological staff (Experimental Officer class), with a corresponding complement of ancillary (Scientific Assistant) grades. These figures would not be much increased after allowing for the other state recruitments. University teaching staff appointments in meteorology have averaged about one per annum in the last decade or so and there is an occasional demand for a research meteorologist in our independent research institutions such as Rothamsted Experimental Station.

The total requirement is then quite modest and that it springs largely from one employer is regrettable in regard to the breadth of opportunity presented to the prospective recruit to the subject. Putting on one side the question whether the scientific and technical health of the community is adequately served by such an intake, one can see that the present need for professional advanced education in meteorology is small compared with most sciences.

The current demands of society for meteorological services form too large a subject for this occasion and fall rather outside my field. They are in large part described in the sequence of *Annual Reports on the Meteorological Office* (H.M.S.O., London). It is certainly not difficult to foresee much wider application of the science to human affairs than is currently made, particularly if the subject progresses on lines we see to be possible (and I am not regarding significant weather modification as an early possibility, except in very limited circumstances). But the wider application of the science deserves quite separate treatment.

3. Education in meteorology

Society accepts the need to provide every school-child with some appreciation, essentially descriptive, of man's atmospheric environment. This is acquired, appropriately enough, in the geography class. For most children their first formal instruction in meteorology is also their last, but they will never cease to have an interest in weather and will often acquire a vital interest so that only the best instruction is good enough. I do not know how good it is today, but from the quality of the Englishman's proverbial conversation (in a university refectory as elsewhere), there seems to me to be scope for improvement. A common mistake, I believe, is to mislead the scholar with spurious explanations or half-truths about weather and climatic processes and I consider that explanation should just not be attempted at the elementary level except as it may derive from the geometry of the earth-sun system, or be evidenced in the maps he studies, e.g., of isotherms and their refraction at coasts because of the difference in the thermal properties of land and sea. Sufficient can and should certainly be said to show that the atmosphere is subject to law. Our own Society might well serve the subject by looking into the quality of elementary meteorological education and making such recommendations as appear

desirable. The Meteorological Office and the British Broadcasting Corporation also have a responsibility at this level of instruction, but for a wider audience than secondary-school children, in order that the television weather map (must it always be a map of isobars ?) and the forecast which accompanies it shall be better appreciated,

The school-child's knowledge of meteorology can, in general, only be developed beyond the elementary level within the sixth-form specialization of geography, which denies physical scope to the treatment. Here and there, however, some attention is given to the subject within the sixth-form curriculum of physics, to meet the demands of certain advanced level examination boards. Now I believe that meteorology can be most effectively used for illustration in sixth-form physics teaching because the atmosphere has a less abstract quality than so much of laboratory physics. The point of the adiabatic concept and of saturation vapour content, to mention just two fundamentals of physics, can be made so obvious by appeal to cloud formation, while electrostatics can be enlivened by showing that the earth and the atmosphere constitute a giant electrical condenser. Moreover, some field study of cloud structure and motion can provide invaluable training in observational skills hardly to be acquired in the rest of the physics course. Yet I do not believe we should press for the inclusion of meteorology *as such* in the sixth-form physics curriculum which must be full enough already. It is primarily as illustration that its value should appear at this stage and I hope physics teachers and examining bodies will be encouraged so to regard it. Meteorologists can assist the process by writing authoritative books for the physics teacher and for the students' leisure reading. They should also do their utmost to ensure that any schoolboy who develops a special interest in meteorology is strongly advised that the path to the science is through physics and mathematics, which is not to deny that the physical geographer may make his contribution to the subject.

There is some urge currently to broaden the basis of sixth-form education so that our ' arts ' men shall know more of scientific method and vice-versa. I am suspicious of the urge, because broadening so often implies shallowness of treatment and lack of mental training. But it is unquestionably desirable for those who are to reach positions of authority in modern technological society to have some appreciation of scientific method and I would expect the science of the atmosphere to be particularly fruitful in such training; because aesthetic and scientific interests might be combined in a common subject and because the atmosphere, as a many-variable, evolving system has more in common with society than most laboratory systems. At this stage we can probably do no more than point out the potential of our subject.

For most students in the United Kingdom the first possible instruction in meteorology as a branch of physical science comes either towards the end of an undergraduate career in physics or, more commonly, in a post-graduate school of meteorology in a university or in the state meteorological service. Physics is now so extensive that an honours undergraduate is hardly expected to cover all its important parts; some selection of material must be made, either without choice for the student or by presenting him with options during his course. Meteorology is such an option for the third-year physics undergraduate at Imperial College and the syllabus is sufficiently comprehensive to enable him to come to grips with the subject – to see what it is about. Moreover, in choosing the option he commits himself to an examination in the subject at the end of the course. I understand that meteorology is such an option at Edinburgh also, and less clearly so at Oxford.

I believe a physicist is made as well by studying meteorology as any other specialization of physics, provided there is a sufficiently broad base of fundamental physics on which to build. Meteorology certainly embraces a wide range of fundamental physics, the descriptive and deductive are both to the fore, and as a scientific study of natural environment it may claim a high educative value. Moreover, the kinds of problems posed by an observational science provide a mental training which can hardly be acquired otherwise; a training which should equip a man to deal successfully with the scientific analysis of almost any many-variable system. Thus the study of meteorology by the advanced physics undergraduate has much to commend it whatever the field he may ultimately engage in. But

I would stress that the study must be sufficiently intense and broad to give the student a feel for the subject as a whole. It is not a subject, at that stage, to peck at.

Unless something of the nature and scope of meteorology can be presented to the advanced undergraduate there is a grave danger that our subject will fail to recruit the best brains and hands, which it undoubtedly requires, against the intense competition for good physicists, theoretical as well as experimental, today. This is indeed our present malaise. Without such presentation there is an even worse danger, that the subject may attract the less vigorous minded. For the meteorology acquired in the geography class at school or by watching television forecasts later does not show the depth of the science except to the very discerning. The problem of attracting good graduates into meteorology would, of course, be much less if high-quality research in the subject were more widely engaged upon in our universities, but the initial momentum is the hardest to acquire. The acquisition of that indefinable quality called glamour would take us some way and this may be realised through the use of rockets and satellites, though not necessarily to the welfare of the subject as a whole. We have no lack of important problems, as I shall presently stress, and it is not obvious that they will receive the greater effort required by adding to them the new problems which will arise from the use of rockets and satellites. There can, however, be feedback.

We cannot expect the number of physics departments which present meteorology as an option, occupying a substantial fraction of the undergraduate's final year, suddenly to increase. The principle of option is still not widely accepted, but if accepted, the meteorologists must also appear on the university teaching staffs. This can only come about by those with enthusiasm for the subject providing the encouragement required in the right quarters. Moreover, there is a minimum size, depending on person and field of work, which will bring viability to a group, particularly in the less theoretical fields. In spite of the obvious difficulties I think that along this path lies the best hope (within the present university framework) for the advance of academic meteorology and, by feedback, of meteorology as a whole. It leaves, however, the problem of presenting the subject to the mathematician untouched.

Some have wondered whether the creation of a first degree in geophysical or cosmic science, with a course necessarily sharing much with that for the physics degree, might not provide a solution to the problem of recruitment to the observational sciences. But I fancy that the ground to be covered would be too great for the normal duration of first-degree courses. I doubt also whether undergraduates would welcome the limitation apparently implied at the outset of their studies to their ultimate choice of a career; unless, *per contra*, space research is to go ahead with the leaps and bounds its most sanguine apologists desire. In this context there is an interesting experiment in progress at Massachusetts Institute of Technology, which has created, under Professor H. G. Houghton, a department and ' graduate degree ' in Earth Sciences. Since the problem of recognition and advance of meteorology appears to exist on both sides of the Atlantic*, this experiment may have important lessons for us.

Formal postgraduate education in meteorology is generally, and I believe rightly, regarded as necessary for those embarking on a meteorological research or advanced technological career in the state services or other bodies. The present United Kingdom demand for such persons has been stated earlier and it is evident that one post-graduate school could provide the training required. Such a school, the only one in a United Kingdom university, exists at Imperial College. It provides a course of one year's duration for honours graduates in physics or mathematics which is recognized by our Department of Scientific and Industrial Research for the award by them of Advanced Course Studentships. After a long experience of this course I think I may claim that an entrant with a first or good second class honours degree should acquire a useful appreciation of the

* The recognition of the lack of impetus in meteorology and the need to accelerate its progress in the United States has led their National Research Council, National Academy of Sciences, to appoint a special committee to advise on national action. The 1958 interim report of this committee, entitled *Education and research in meteorology*, makes far-reaching proposals which are worthy of our attention.

physical (including dynamical) problems of the atmosphere, particularly below about 50 km where our knowledge and understanding are greatest. It is a course which will fit him to embark on research on almost any part of meteorology with the important asset that he should be able to see his particular research problem in relation to the subject as a whole. I cannot too strongly emphasize how important I regard that asset to be. Without a formal training the researcher is liable to waste much effort and time in reaching the stage of distinguishing the trival from the significant, the distinction requiring more insight in an observational than an experimental science. The course I have described is also intended to equip a man for the advanced technological employments of meteorology but without regard to the conventional details of procedure in such employ.

The Department of Meteorology at Imperial College is not, however, the only post-graduate school of meteorology in the United Kingdom, for the Meteorological Office has its own training school for those officially recruited at honours graduate as well as at lower level. Inasmuch as diversity of method, in education as in other activities, may be stimulating and even necessary, the existence of more than one post-graduate school can be welcomed even though numbers do not currently demand it. Nevertheless, as a far from detached observer, I do regret that, for the sake of meteorology, there are some entrants to our services who are denied their post-graduate training in the stimulating atmosphere a university should provide. Furthermore, I wonder whether the inflow of high-class physicists and mathematicians to the meteorological service may not have been adversely effected by such people's fear, sound or ill-founded, of unnecessary isolation at a critical stage of their scientific career. One Commonwealth country at least has shown that training following recruitment into its service can be carried out in the university.

The Department at Imperial College is not of course wholly concerned with formal education either of physics undergraduates, under the option scheme, or of graduates who may or may not go on to the Meteorological Office. It trains many from overseas, from the Commonwealth and elsewhere, and like any other university research unit, welcomes any qualified student of capacity for research. In this regard, there is no reason why a student undertaking research in meteorology should feel limited in his later career, for the research training is valid for much more than meteorology, as experience too amply shows. He may be somewhat irked by undertaking further formal study after graduation but the student of real capacity need not much delay his contact with research on that account. He certainly will not do so if he has had the benefit of following an undergraduate option in the subject.

I have said little of meteorological education outside the formal paths and shall add no more than that I think our Society is already exercising a worthy concern for its responsibilities in this matter, particularly in its publication *Weather** and through its co-operation with the Field Studies Council. University departments are, I think, complementing these activities satisfactorily through extra-mural work.

I have nothing to say of meteorological education through geography at the university because this subject has been sufficiently aired in recent discussion. Effective recruitment to the science cannot, I feel sure, come by this path.

4. Research in meteorology

I come now to the research problem and particularly to the inadequacy as I see it of the research effort in meteorology as a whole (the high levels of the atmosphere are not however lacking attention) and not least in our universities.

On the broadest basis it may be said that meteorological research is prosecuted in about twelve of our twenty-four universities, which may appear quite healthy. But in only a small proportion of the twelve is the effort on any appreciable scale, and it is certainly

* Like my predecessor, Dr. Sutcliffe, I would welcome an enlargement of horizon beyond that implied in the title of our semi-popular periodical. An appropriate change of title and scope might materially help to attract the more adventurous or wide-minded student to our science and the Society.

not commensurate with the magnitude of the problems posed by the atmosphere. This is evident, for example, by observing how few are the university sources of our current meteorological research literature, particularly on problems below the ionosphere.

It is indeed fortunate for the state of our science in the United Kingdom that the effort applied to research by the Meteorological Office has increased tremendously since the last war. This research must necessarily reflect to some extent the practical problems facing a state meteorological service but I see no sign of its being straight-jacketed to utilitarianism. It is, however, noteworthy that the published research of the Meteorological Office over the last decade or so has largely emanated from those who were already professional meteorologists at the end of the last war. The new generation has not yet, I think, made its impress on the subject and this I believe to be a clear danger signal to us. Research is primarily the activity of the young and it is to be presumed that they have been given their chance.

A tremendous growth of meteorological research took place in the first decade after the last war in many countries and the British meteorologist made a notable contribution to it. I believe the growth in this country sprang from two main sources, the creation during the war of a running three-dimensional exploration of the atmosphere by aircraft, radiosonde and radar-wind, and the war-time recruitment of many physicists and mathematicians who, immediately concerned with operational duties, acquired knowledge of the ways of the atmosphere and, when later given the opportunity, used their experience in the effective formulation of problems and in their solution. Descriptive synoptic meteorology and dynamical meteorology benefited particularly, but cloud physics, radiation and turbulent transfer notably advanced also. The study of the high atmosphere was simultaneously expanded, mainly by funds made available by a wise and benevolent Air Ministry to the Royal Society who, through their Gassiot Committee, sponsored much of this work. It will also surely be agreed that the creation for the first time in this country of a sizable university department of meteorology, that at Imperial College, paid handsome dividends in research. (The last three Buchan Prizewinners of this Society came from that department). Not least, the emergence of the electronic digital computer provided so invaluable a tool as literally to open up new worlds of theoretical endeavour in the subject.

Yet we do not appear to be building adequately on that fine post-war effort whose energy, in the more conventional but challenging aspects of the subject at least, seems somewhat to be spent, though challenging problems continue to abound. I have already referred to the too small community of bright young men on the meteorological scene and another indication, for what it is worth, is the decline, by about a quarter, in the size of our own *Quarterly Journal* since 1951. Some may say that the subject is so difficult that progress like that of the immediate post-war years cannot be expected to be maintained. I do not much share this view. While the subject is unquestionably difficult its problems are rather well formulated in the broad – though our minds must be open to profitable recasting – and their difficulty can be a stimulus. No doubt the cream has been skimmed from the radiosonde networks but new kinds of observations can be conceived and they do not necessarily require to be made on a wide scale to bring large profit to the subject. Perhaps the observations of the International Geophysical Year and particularly the more novel of them will provide a major stimulus to the subject.

Whatever the correct reading of the signs there is, I submit, no doubt that we are failing to attract the good young minds in numbers sufficient to make a continuing impact on the subject. We are failing to communicate the high quality of our science, to make it sufficiently recognised in our universities. The war-time recruitment obscured our failing in the universities and we should now do all we can to remedy it.

How then, are we to convey to others the tremendous worthwhileness of the problems of the more conventional kinds of meteorology ? (I have the feeling that high-atmosphere meteorology is in no need of such an apology, because it is relatively new, largely empirical, with exciting new techniques to exploit). The question is one I hope the Society will

consider, collectively or individually, and then proceed to action. For the present I think I cannot do better than give my own partial view of the current state of the science and of some of the worthwhile problems immediately ahead of us.

We know that the continuously changing physical and chemical state of the atmosphere arises from and gives rise to many classes and scales of motion, under a solar energy input with properties well enough defined except in the very short wavelengths of concern in the high atmosphere. The geometrical, physical and chemical properties of the earth's land and sea surface provide boundary conditions to the atmospheric evolution which are not, however, independent of that evolution. Our problem is broadly to have such an understanding of the mechanism of atmospheric processes that, given the physical and chemical state at any 'instant' or 'succession-of instants', we can say into what further states it will be transformed on time-scales stretching from minutes to geological epochs – the cosmogeny of the atmosphere. Thus posed, the problem of meteorology, as indeed of most science, is ultimately a problem in forecasting (it may also be in 'back-casting'). It is a great objective and a tremendous mental and technical challenge is implied. Clearly it is a matter of imaginative definition (or empirical test) to say what shall constitute an adequate description of instant and state for any particular time-scale or space-scale involved.

Any scientific forecast must be contained within a probable error and a science achieves its aim in so far as that error is acceptable for the purpose for which the forecast is made. Thus, we could probably get within about 10 per cent of the absolute temperature of the air at any point below about 50 km by working out the radiative equilibrium temperature, given the composition. But this would be regarded as hardly worth doing, because the temperatures we observe, suitably averaged, would provide a much better estimate for other times and because an atmosphere in radiative equilibrium would have no wind and no rain, nor would it evolve except in direct sympathy with the solar radiation. Moreover, to assume the composition would to be beg one of the major questions of meteorology.

Our present working hypothesis is that the atmosphere – its electric and magnetic properties apart – can be treated as a fluid continuum with aerosol, and that its behaviour is expressed by Newton's laws of motion (for the gaseous component, in the form of the Navier-Stokes hydrodynamic equations adapted to a rotating frame of reference), by an equation of state and by the equations for continuity of mass and energy. These are sufficient for the independent variables involved. However, the equations demonstrate, what we know from observation, that atmospheric motion must be turbulent, with a wide spectrum of motions by no means similar in different parts of the spectrum. Some averaging of the equations is therefore necessary before useful solutions may be obtained, the method and scale of averaging depending on the nature and scale of the problem considered. A big difficulty immediately arises. Because of their non-linearity, the equations, by the averaging process, acquire new terms (turbulent-flux terms such as Reynolds or Jeffreys stresses) and superficially it would appear that solutions for one scale or type of motion must wait on the availability of solutions for all smaller scales of flow or else some additional hypothesis or law is needed to obtain solutions. It is ironic that by engaging to forgo knowledge of detail our problems become formally more complex.

I have thus briefly stated the starting point of deductive meteorology. What of the descriptive element; the material on which the equations may operate? On one scale at least, that of the radiosonde network, the meteorologist is indeed rather well served with the major variables up to about 20 or 30 km. There are big gaps in the network, over the oceans and the less densely populated parts of the globe, but the International Geophysical Year will have given for a substantial period a more complete description than would otherwise have been available. That perennial problem, water vapour, remains with us except when a research aircraft is available (and condensed water vapour is still then a problem), but the limitations of most hygrometers can hardly be accounted a major stumbling block to the immediate development of the science. For smaller-scale studies

than the radiosonde network is serving, *ad hoc* methods of observation can be, and are, devised; they will assuredly be extended in space and time as research shows their potential for further reward.

I would not give the impression that I think data are merely required as the food of equations. There is, on the contrary, great scope for the inspired observation as an aid in determining how our basic equations are to be made more usable; in the construction of models in fact. Thus I believe we may be entering a phase of specially significant observation of trace substances – water vapour, ozone, radioactive material, and so forth – which will help to clarify the problem of fronts, jet streams, the tropopause and exchange of substance between stratosphere and troposphere. Again, our descriptive knowledge of cloud structure is quite rudimentary and leaves scope for continuing skilled observation. We may also expect the advances in infra-red spectrography to be increasingly applied to the study of atmospheric radiation, particularly of its transformation with height, for we have yet to provide the energy conservation equation with a generally usable form of the radiative energy-source term.

Returning now to the deductive aspects, we have qualitative theories of atmospheric behaviour on a number of scales and quantitative theories of a very few. Thus the fact that realistic evolutions of the large-scale extra-tropical atmosphere may now be computed for one or two days is progress indeed. This progress results from appropriate simplifications of the basic equations, from model construction in fact, and the advent of electronic digital computers which are almost bound to give greatly increased scope to what is rare in an observational science, the experimental method. Theory is less well advanced in the treatment of larger- and smaller-scale processes than the above, but the first Napier Shaw Prize essay gave reason for optimism on the general circulation; there is a useful similarity theory of small-scale eddy transfer processes near the earth's surface and, for free convective heat transfer in dry air, something better than similarity theory. Wet convection, vertical or sloping, from the cumulonimbus to the depression, has not yet responded to treatment, in part I think because description should first go further. On all these scales and types of behaviour, the increasing study of laboratory models is to be welcomed as an aid to the development of theory.

Our lack of theory of a number of kinds of atmospheric behaviour is reflected in our lack of a comprehensive theory of climate, i.e., of the general circulation, for global climate is an integration of the effects of almost all smaller-scale processes. We shall have made impact indeed on our subject when we are able to demonstrate the necessity of the observed longer-term fields of temperature, rainfall, and wind on the global scale, or to be less ambitious, what they should be on an earth of uniform surface. Yet we do not have to wait on understanding all modes of atmospheric behaviour to make significant progress on the global problem. In particular I welcome two current lines of approach to general circulation study, both descriptive, which may notably contribute to the theory. The first is the study of the evolution of the fields of atmospheric properties smoothed on time scales increasing upwards from days to weeks, so as to bridge the gaps in known behaviour of the atmosphere between the daily synoptic and the seasonal; the study in fact of the manufacture of climate from weather. Such study is no longer new but it appears to me to have been so much conditioned to the problem of long-range weather forecasting – outside this country more than within it – as to have acquired a false perspective. Meteorology, because of its wide application to human affairs, is ever in danger – it frequently succumbs – of attempting to apply its knowledge before it is ready to do so. (Distortion of problem may also ensue). This brings the subject into scientific disrepute among those unaware of the nature of our science and it has, I believe, something to do with the hesitation of our universities to give it greater encouragement and of the dedicated graduate to take it up. A sustained effort in this particular study is to be welcomed even though a practical dividend is very late to appear.

The second approach to the general circulation to which I would refer is the study of climatic variation, for variations of the object studied may be as suggestive as dissection

of the type. We know much in a disjointed way about climatic variation, but a global integration of the data, on any time scale, hardly begins to appear. Yet a global appraisal is so necessary to see the problem to be solved. The enterprise would indeed be large but is ripe for tackling. I can imagine no better substitute for the experimental method, usually so potent in science but difficult of application in meteorology, than the study of anomalies of atmospheric and boundary properties on a global scale, from year to year, decade to decade, and so forth. When other planetary atmospheres become more accessible to observation – the day is presumably not so distant – the method of comparison can be appropriately extended. The techniques involve the well tried synoptic and the novel dating procedures, natural thermometers, and the use of glaciological, oceanographic, botanical and geological material among others. A disciplined drawing together of so many threads might prove as rewarding for other sciences as it should be for our own and the stimulus and enjoyment of the enterprise are, I hope, clear to see.

Other branches of meteorology provide in my view equally stimulating prospects but I do not have space to particularise, except to express a view about high-atmosphere meteorology. This field, as I have said, seems clearly destined for increasing effort, not least from a growing use of rockets and satellites. I welcome the increase in interest in the field and would be delighted if it were attended by those working in it identifying themselves more whole-heartedly with this Society, which it seems to me is the learned body appropriate to the field. The subject, is, of course, at this stage in a very different condition from that of the much more fully-explored lower levels of the atmosphere and new kinds of process – photochemical, magnetohydrodynamic, etc. – are concerned. It is still in the stage of first exploration in which nearly every observation is exciting for itself, almost regardless of the integral pattern which will more slowly emerge. But the chief challenge of an observational science is the integration of observation and it is very probable that the interesting behaviour in the high as in lower levels will turn out to be global and evolutionary in character. I surmise indeed that the subject will pass rather quickly from a quasi-static to a dynamic type of meteorology and this I hope will help to provide the bridge that needs to be built for the integrative good and further blossoming of meteorology.

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Seasonal and other temperature changes in the Antarctic atmosphere*

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(Manuscript received 7 November 1958)

Summary

The annual variation of temperature in Antarctica has interesting properties : it is largest in the stratosphere (50° to 60°C), smaller at the surface (20° to 40°C) and smallest in the troposphere (10°C). During the winter night the troposphere temperature decreases only slightly while the stratosphere temperature drops steadily at about ¼°C per day. This differential cooling, which weakens and at times wipes out the tropopause, is caused, on the one hand, by intense horizontal advection of maritime air into the Antarctic troposphere, and , on the other hand, by very little advection through the strong stratospheric jet stream encircling Antarctica.

This ventilation of the Antarctic troposphere by warm marine air causes large portions of Antarctica to exhibit the *kernlose* winter-temperature curve instead of the sharp winter minimum usually found in polar continental climate. Anomalously high June temperatures in the lower troposphere at Little America are attributed to intense cyclones which form in the Ross Sea area and advect air from the lightly ice-clad or open ocean located not too far north of the Ross Sea.

Large deviations in average monthly temperatures are found in the Ross Sea area which are undoubtedly a reflection of large year-to-year circulation changes in that area.

The Antarctic and Arctic stratospheres exhibit quite different temperature behaviours after the winter solstice. The Antarctic stratosphere continues to cool until the sun returns and then warms as much as 50°C in 1 month. On the other hand, the Arctic stratosphere exhibits a warming of 30° to 40°C, sometimes beginning 6 weeks *before* the sun returns.

A secular trend of temperature since 1912 of + 2·6°C at Little America (78° 12′S, 162° 15′W) compares with a + 6·2°C trend at Spitsbergen (78° 04′N, 13° 38′E).

Finally, temperature and outgoing radiation observations made at the South Pole I.G.Y. Station during the cold period of 19-24 April 1958 are presented to illustrate quantitatively the important effect of warm cloud radiation on surface air temperature and its vertical gradient.

1. Introduction

In this paper five properties of temperature patterns in Antarctica will be described and compared with their Arctic counterparts : (i) seasonal temperature changes and the *kernlose* winter; (ii) year-to-year variations; (iii) a warming trend in annual temperatures at Little America since 1912; (iv) stratospheric cooling and warming; and (v) a case history showing the strong influence of clouds on surface air temperature and its vertical gradient during the winter night at the South Pole.

2. Seasonal temperature changes

The aerological soundings made by the Norwegian-British-Swedish Expedition at Maudheim in 1950-51 (Schumacher 1955) confirm and extend in a striking manner earlier conclusions regarding the variation of the annual range of temperature with altitude (Wexler 1950). In this latter paper it was shown that at latitudes from 40°N-73°N (the northernmost limit of the data) the annual range diminished from 20°C-35°C at the surface to a minimum of 15°C-20°C at 3-6 km. Another minimum was found at the tropopause and above this, in the stratosphere, the annual range increased with height to 19 km, the upward limit of the data.

The Maudheim observations at 71°S show an even larger variation of the annual range with height, as indicated by the curve in Fig. 1, drawn from data presented in Schumacher's paper. The minimum range of 7°C, found throughout most of the troposphere, is sandwiched in between maxima of 23°C at the surface and 50°C at 50 mb.

* A slightly expanded version of a paper given at the Symposium on Antarctic Meteorology, V General Assembly, C.S.A.G.I., Moscow, U.S.S.R., 8 August 1958.

† Chief Scientist, U.S.–I.G.Y. Antarctic Program, National Academy of Sciences, Washington, D.C.

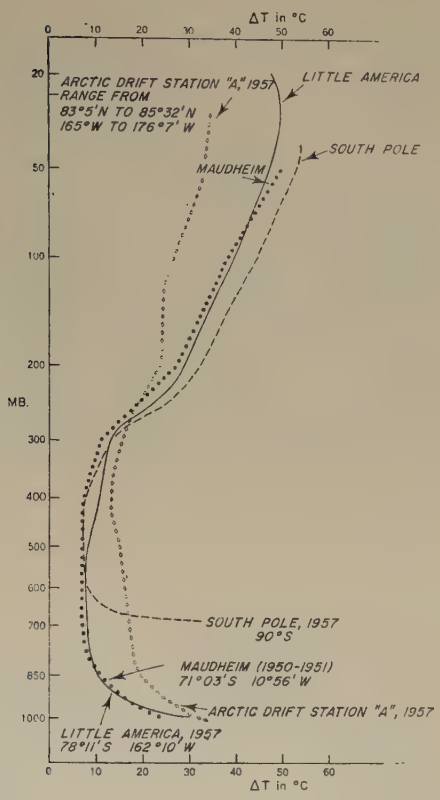

Figure 1. Vertical profile of temperature difference between warmest and coldest month for the South Pole, Little America, Maudheim (Antarctica) and for Drifting Ice Station 'Alpha' (near 83°N, 160°W).

In Fig. 1 curves are drawn for the Little America and South Pole Stations for 1957. Taking into account the greater elevation of the South Pole we observe a striking similarity in these curves despite the fact that two of them are located on opposite sides of the continent and the third deep in the interior.

The large temperature ranges at the surface and the stratosphere are caused by prolonged heating by solar radiation during the polar day and cooling by loss of radiation during the polar night. During the polar day, despite the high albedo of near 90 per cent, the snow surface absorbs enough energy to weaken considerably or destroy the surface-temperature inversion. Likewise stratospheric ozone present in large amounts in late winter and spring, as shown by data from Little America (78° 11'S, 162° 10'W), (Moreland 1958) and unpublished data from the Royal Society Station at Halley Bay (75° 31'S, 26° 36'W), absorbs ultra-violet radiation from the sun and becomes warmer. (See Fig. 10 for station locations).

During the polar night the snow surface, radiating as a black body, cools more rapidly than the overlying cloudless atmosphere and forms the characteristic polar inversion (Wexler 1936). In the stratosphere, ozone, water vapour and carbon dioxide emit infra-red radiation; therefore during the polar night the air at 50 mb (18-19 km) at the South Pole and also at Ice Station 'Alpha' at 83°N 160°W, cools on the average 0·23°C day^{-1}, in quite good agreement with Gowan's (1947) rate of 0·3°C day^{-1} for the initial cooling of the 15-20 km layer after the sun vanishes.

Also shown in Fig. 1 is the profile of the annual temperature range for Arctic Drift Station 'Alpha' during its motion in 1957 between latitudes 80° and 85°N; this profile has a shape similar to the Antarctic profiles but with some interesting differences : the

tropospheric amplitudes are double those in the Antarctic while the stratospheric amplitudes are only 0·7 as large. The larger amplitude in the Arctic troposphere is caused primarily by intense summer heating and winter cooling over the nearby continents which influence the atmosphere over the Arctic Basin. Similar conditions are not found in the ice-covered Antarctic Continent most of which is located thousands of miles from other continents.

The larger temperature amplitude observed in the Antarctic stratosphere is caused by colder winters and warmer summers. The winters are colder because, as will be illustrated later, there is very little warm air advection through the strong stratospheric jet-stream encircling Antarctica, thus permitting the temperatures to fall steadily in close agreement with the theoretical radiative rate of Gowan. The summer is warmer because the albedo over Antarctica (80-90 per cent) is much higher than that over the Arctic ice pack (50-60 per cent) with its many water leads. The high intensity of the reflected solar radiation permits the ozone in the Antarctic stratosphere to have a second chance to absorb the Chappuis bands of the solar radiation and thus achieve a higher temperature (Wexler and Moreland 1958).

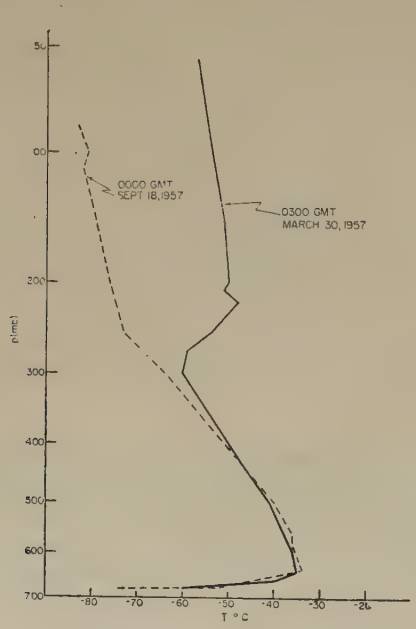

Figure 2. Upper-air soundings at the South Pole (I.G.Y. Station) near the beginning of the polar night and at the end of the polar night (after McCormick 1958).

Two individual and representative soundings at the South Pole Station, one taken at the beginning of the polar night and the other at the end, illustrate the remarkable difference between stratospheric and tropospheric response to the absence of the sun (Fig. 2). It is this 'differential' cooling between stratosphere and troposphere which weakens and at times obliterates the tropopause during the Antarctic night.

The reason for this differential cooling is found in the great difference in flow pattern between the troposphere and stratosphere. The Antarctic winter troposphere is characterized by vigorous meridional motions and strong heat advection into the continents which compensates for the radiative-heat losses, as illustrated by average contours for July 1957 at 700 and 500 mb taken from Rastorguev and Alvarez (1958), Figs. 3 and 4. In contrast, the stratospheric flow pattern as revealed by the average 300 mb contours (tropopause) and the 50 mb contours (drawn from daily charts analyzed by W. B. Moreland), Figs. 5 and 6, show a strongly zonal flow with a jet stream encircling Antarctica.

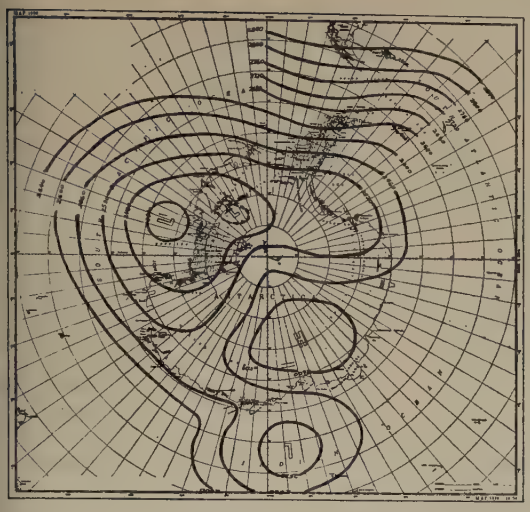

Figure 3. Average contours, 700 mb July 1957 (after Rastorguev and Alvarez 1958).

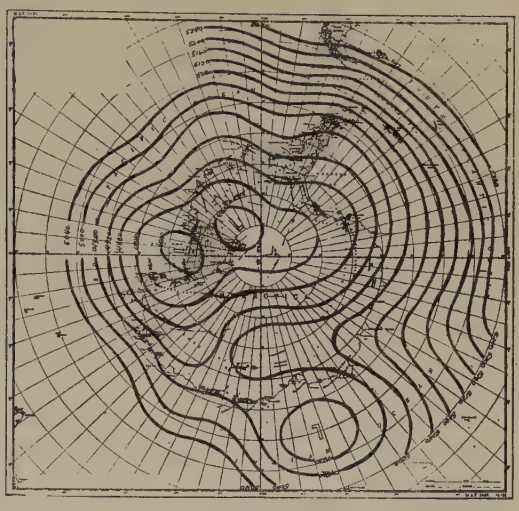

Figure 4. Average contours, 500 mb July 1957 (after Rastorguev and Alvarez 1958).

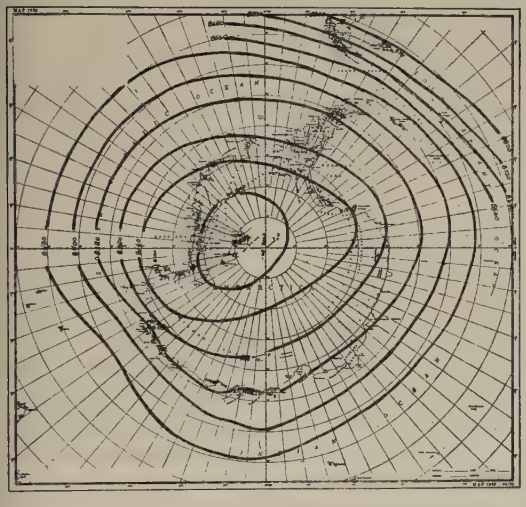

Figure 5. Average contours, 300 mb July 1957 (after Rastorguev and Alvarez 1958).

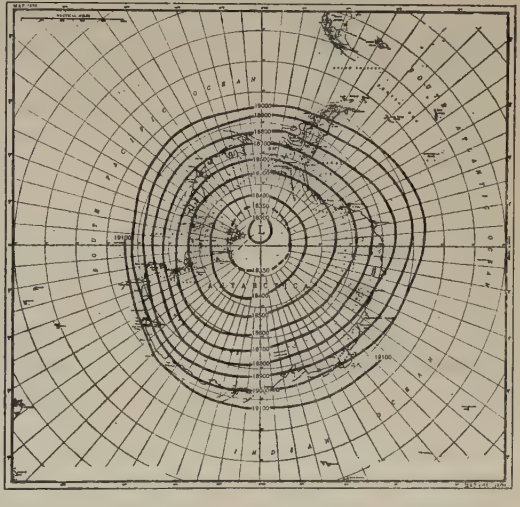

Figure 6. Average contours, 50 mb July 1957

The striking contrast in the thermal properties of the troposphere and stratosphere is further illustrated in the average June 1957 vertical cross section extending from the South Pole to Canton Island (2° 46′S) along roughly the 170°E meridian (Fig. 7). In the troposphere above the surface layer, the isotherms are practically horizontal from the Pole to lat. 70° and then begin to rise, with the largest gradient found near 30°S. In contrast to the near barotropic state of the Antarctic troposphere between 700 and 300 mb the stratosphere is strongly baroclinic, with a large temperature gradient from the Pole to latitude 50°*.

* Evidence for additional months is given by R. C. Taylor : 'Mean monthly meridional cross-sections of temperature from the South Pole to the North Pole near 170°E – A preliminary report,' presented at the Antarctic Meteorological Symposium, Melbourne, Australia, 18-25 February 1959.

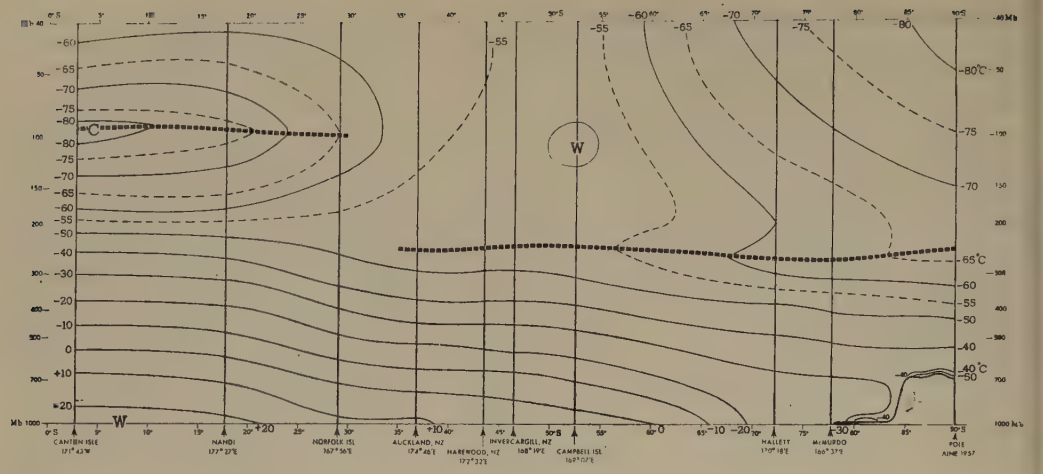

Figure 7. Vertical cross-section through the atmosphere, South Pole to Canton Island, June 1957.

It might now be asked why does not warm-air advection compensate for the stratospheric radiative cooling in much the same manner as it does in the troposphere – particularly since the N-S temperature gradient in the stratosphere observed in the winter (see Fig. 7) is larger than in the troposphere and would thus be a de-stabilizing influence ? The answer appears to be that the greater thermal stability of the stratosphere compared to that in the troposphere (see Fig. 2) discourages the release of baroclinic instability into the large-scale westerly meanders and eddies that are found in the troposphere. Calculations using Fleagle's (1957, 1958) criterion for baroclinic instability which bear out this reasoning will be made the subject of a separate paper.

3. The *kernlose* winter

The *kernlose* pattern of winter temperatures first observed in the Arctic Basin (Pollog 1924) but also present on the Greenland Ice-cap, is found to be surprisingly prevalent in Antarctica, not only at coastal stations but deep in the interior (Wexler 1958a) Not only is the broad flat winter minimum found but there are frequent reversals of the expected temperature decline or increase, in extreme cases amounting to nearly 10°C.

This phenomenon is further illustrated by the average monthly temperatures for 6 years of Little America data shown in Fig. 8, together with the average curve for Verkhoyansk, Siberia. We see that Little America has a flat winter minimum in contrast to the typically sharp polar continental minimum at Verkhoyansk. Six of the seven years of Little America temperature data show the winter maximum in June; the preceding minimum is found in April for two years and in May for four years.

In Antarctica, during 1957, a large number of stations, coastal and interior, especially those in the Ross Sea area and in interior regions to the west, showed marked *kernlose* patterns of winter temperatures. This is illustrated in Fig. 9 where of the nine curves of monthly mean temperatures, seven show a *kernlose* pattern with early winter reversals of the expected temperature decline. The most striking reversal is that of Little America where the first minimum temperature was reached in April, — 33°C, followed by a rise to — 31°C in May and to — 24°C in June. McMurdo Sound and Cape Hallett, two other coastal stations, show less marked patterns. But four interior stations, the South Pole (2,800 m a.s.l.), Byrd (1,500 m), Charcot (2,400 m), and Pioneerskaya (2,700 m), also show the *kernlose* pattern with significant reversals. The two remaining stations in the figure, Dumont D'Urville and Wilkes, located on the coast of Wilkes Land, show a *kernlose* pattern with no temperature reversals. Station locations are shown in Fig. 10.

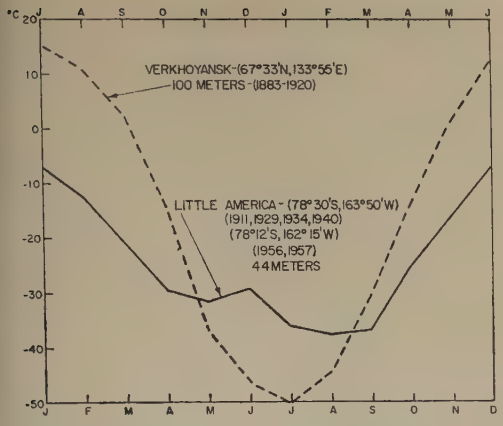

Figure 8. Monthly mean temperatures at Verkhoyansk and Little America.

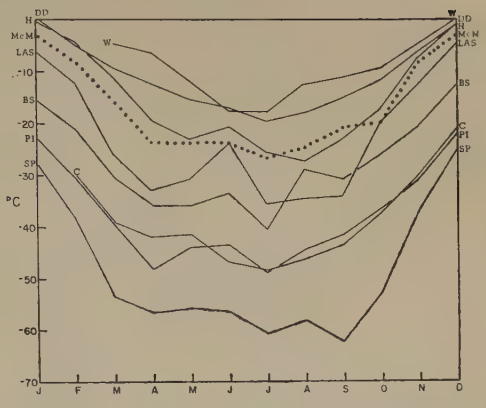

Figure 9. Annual variations of mean monthly temperatures at coastal and interior stations in Pacific Sector of Antarctica (1957). (W – Wilkes; DD – Dumont D'Urville; H – Hallett; McM – McMurdo; LAS – Little America Station; BS – Byrd Station; C – Charcot; PI – Pioneerskaya; SP – South Pole). (For locations see Fig. 10).

In the Weddell Sea area (Fig. 11) the *kernlose* pattern was weak at the Belgrano, Royal Society, and Ellsworth Stations in 1957 but was strongly present with large reversals at Belgrano, Shackleton (data not shown in Fig. 11) and Royal Society in 1956 (before Ellsworth was established) and at Belgrano in 1955, when this was the only station in the area.

If the phenomenon of the June temperature maximum, so noticeable at Little America, were characteristic of the surface only, then an explanation in terms of higher wind speed or greater cloudiness might be acceptable. However, average monthly upper-air temperatures for Little America, shown in Fig. 12, indicate that the anomalously high surface temperature observed in June 1940, 1957, and 1958 is also found aloft but diminishing with height until very little sign of them appears at 500 mb and higher levels. (To decrease the number of curves the average of the curves for the combined 3-yr period is shown but the effect is found in each of the three years, 1940, 1957, 1958). In 1956, when the June surface temperature was lower than May or July the lower temperatures were also found for all levels up to 300 mb.

Figure 10. Map of Antarctica showing station locations mentioned in text.

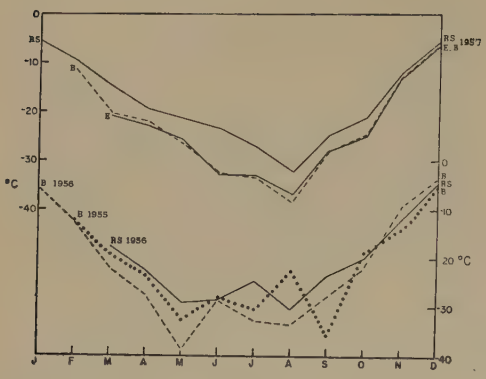

Figure 11. Annual variations of mean monthly temperatures for stations in the Atlantic Sector of Antarctica. (RS – Royal Society (Halley Bay) Station; B – Belgrano; E – Ellsworth). (For locations see Fig. 10).

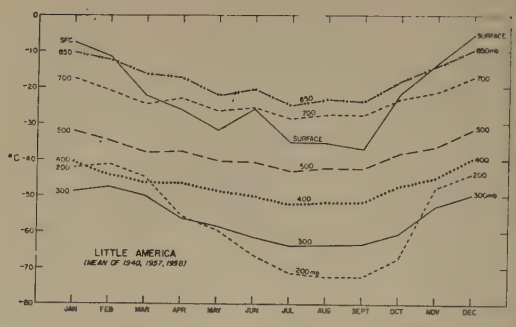

Figure 12. Average monthly temperatures, surface and aloft, Little America, 1940, 1957, 1958.

Thus it appears that the occurrence of an anomalously warm June is not restricted to the surface but is found also throughout a major portion of the troposphere. Therefore we must look for an explanation not restricted to local conditions of cloudiness and wind speed but based on large-scale circulation changes in Antarctica and environments.

An attempted explanation of the Antarctic *kernlose* winter and the tendency for a mid-polar night temperature maximum is given along the following lines : as the sun sets, the temperature drops rapidly over the continent but less so over the surrounding oceans which are only partly ice-covered. The increasing meridional temperature gradient brings about the release of baroclinic instability in the troposphere which initiates the formation of numerous intense cyclones. These cyclones move vast quantities of warm marine air southward in the lower troposphere, effectively ' ventilating ' large portions of Antarctica above a thin surface layer of cold air and slowing and even sometimes reversing the normal seasonal decline in surface temperature.

As winter proceeds, a thicker and wider ice-pack extends hundreds of miles to the north of Antarctica (Anonymous 1957) and materially lowers the temperature of the southward-moving air masses, thus encouraging a second drop of temperature, near the surface and aloft, so that the lowest surface temperatures are usually found well after the winter solstice, sometimes as late as September.

4. Year-to-year temperature variations

As already indicated in Fig. 11, there are large year-to-year temperature changes in Antarctica. This is further illustrated by average monthly temperatures observed in 1957 and 1958 at Little America, Byrd, and the South Pole Stations (Fig. 13).

Whereas the April 1958 temperature at Little America was 11°C higher than in 1957, the South Pole temperature was 5°C lower. In August of 1958, Byrd Station was 13°C colder than in August of 1957.

The average monthly temperatures at Little America show the following mean deviations (Table 1). (The mean deviation is defined as the arithmetic mean of the differences from average taken irrespective of sign).

The mean deviation for Little America is largest for June (4·2°C) and smallest for January (1·3°C). April, August and September also exhibit large year-to-year changes. The maximum deviation in June is especially significant in view of the strong warm-air advection which on the average renders this month 2·2°C warmer than May.

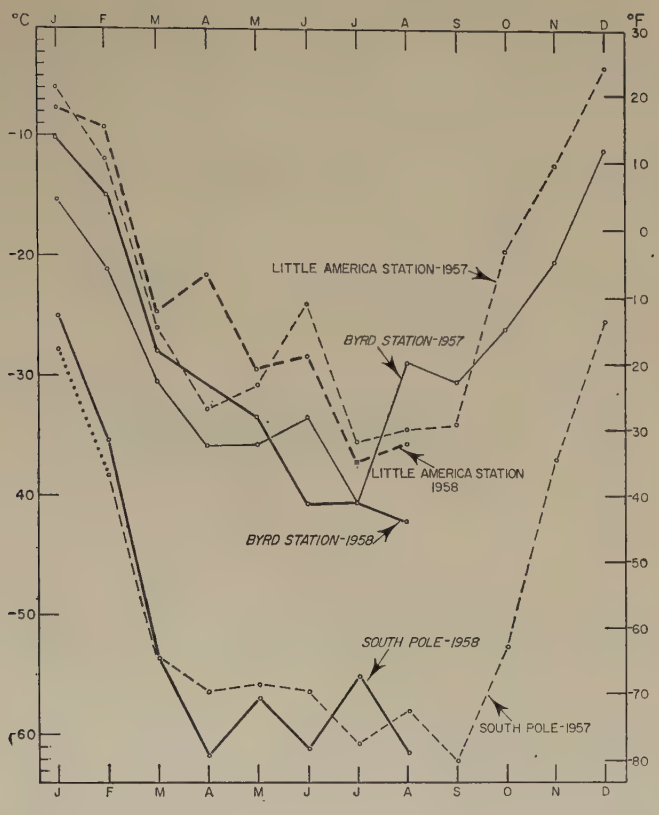

Figure 13. Average monthly temperatures, 1957 and 1958, at Little America, Byrd, and the South Pole.

Also shown in Table 1 are mean monthly temperature deviations for McMurdo Sound stations and for Laurie Island (60° 44′S, 44° 39′W), as compiled by Meinardus (1938). At all three stations the deviations are largest in the period from March or April to October, with the Little America values in general being the largest. The Little America deviations compare quite well with those at Bismarck, North Dakota, a station noted for its large changes from year to year (Thom 1955, Nagao 1951).

TABLE 1. MEAN DEVIATIONS OF MONTHLY TEMPERATURES

	Little America (1911, '29, '34, '40, '56, '57, '58)		McMurdo Sound (5 years)	Laurie Island (1903-34)	Bismarck N. Dak. (1921-50)	
	No. years	Average temp. (°C)	Mean deviation (°C)			
Jan.	7	− 7·4	1·3	1·1	0·6	1·4 July
Feb.	5	− 12·4	1·7	1·7	0·7	1·2 Aug.
Mar.	7	− 21·8	3·2	1·5	0·7	1·5 Sept.
Apr.	7	− 28·4	3·7	2·3	1·6	2·0 Oct.
May	7	− 31·3	2·4	1·8	2·7	2·1 Nov.
June	7	− 29·1	4·2	1·7	2·8	2·8 Dec.
July	7	− 36·4	2·8	3·4	2·6	4·0 Jan.
Aug.	7	− 37·9	3·6	2·5	3·1	4·0 Feb.
Sept.	6	− 36·9	3·5	2·5	2·0	2·2 Mar.
Oct.	6	− 24·9	2·4	2·7	1·7	1·8 Apr.
Nov.	6	− 15·9	1·9	0·9	1·1	2·0 May
Dec.	6	− 6·4	1·4	1·3	0·6	1·5 June

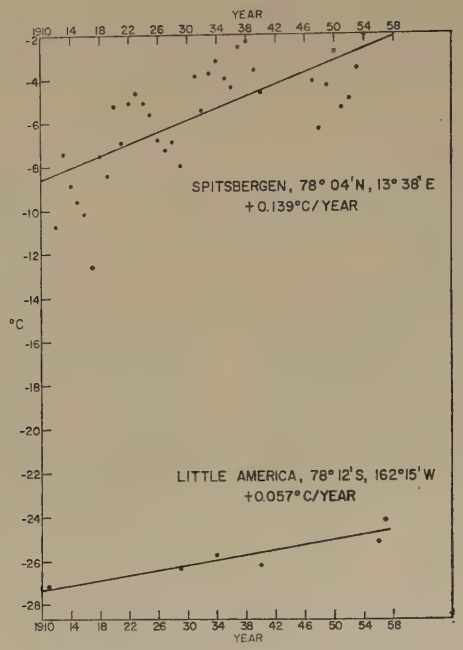

Figure 14. Temperature trends at Little America and Spitsbergen.

5. Warming trend at Little America

Various camps have been established in the eastern portion of the Ross Ice Shelf and located a few kilometres from the barrier or edge of the shelf ice. The first was Amundsen's Framheim base of 1911-12, followed by the various Little America stations of the 1929-30 and 1934-35 Byrd Expeditions, the 1940-41 U.S. Antarctic Expedition and the 1955-58 U.S.-I.G.Y. Little America V Station. All these stations are located within 50 km along a SW-NE line parallel to and about 3 km from the barrier. The flat surface and absence of exposed rock or nearby mountains enables the observations from each of the camps to form a homogeneous temperature record whose period covered and representativeness are unequalled elsewhere in the Antarctic. Although temperature observations have been made at various camps on Ross Island in McMurdo Sound, the nearby and irregular distribution of land, ice, exposed rock, bay ice, shelf ice, and open water renders incompatible temperature observations made by the various expeditions in the McMurdo Sound area.

The average annual temperatures for Little America, plotted in Fig. 14, show a significant warming trend of 2·6°C since 1911. If temperature data for each of the intervening years were plotted there would, of course, be much more irregularity than displayed by the six years whose annual temperatures fall so nicely on a straight line.

Compare this warming trend at a station 78°S with one at 78°N – Spitsbergen, whose average annual temperatures since 1912 are also plotted in Fig. 14. Here the trend is more than twice as large as Little America's, 6·2°C compared with 2·6°C. Additional evidence supporting the reality of the warming trend at Little America is presented in another paper (Wexler 1959) but suffice it to say that each station shows a high correlation with a linear trend line : 0·72 for Spitsbergen (significance level 0·001) and 0·92 for Little America (significance level slightly less than 0·01). Also the 1958 average temperature for Little America fell exactly on the trend line established by the previous years.

The Spitsbergen warming probably represents an extreme condition of a climatic change which is believed by some to encompass the entire Arctic Basin (Ahlmann 1948). Whether Little America is a representative or an extreme example of a similar warming trend in the Antarctic cannot be determined in absence of similar long and reliable records elsewhere on the continent.

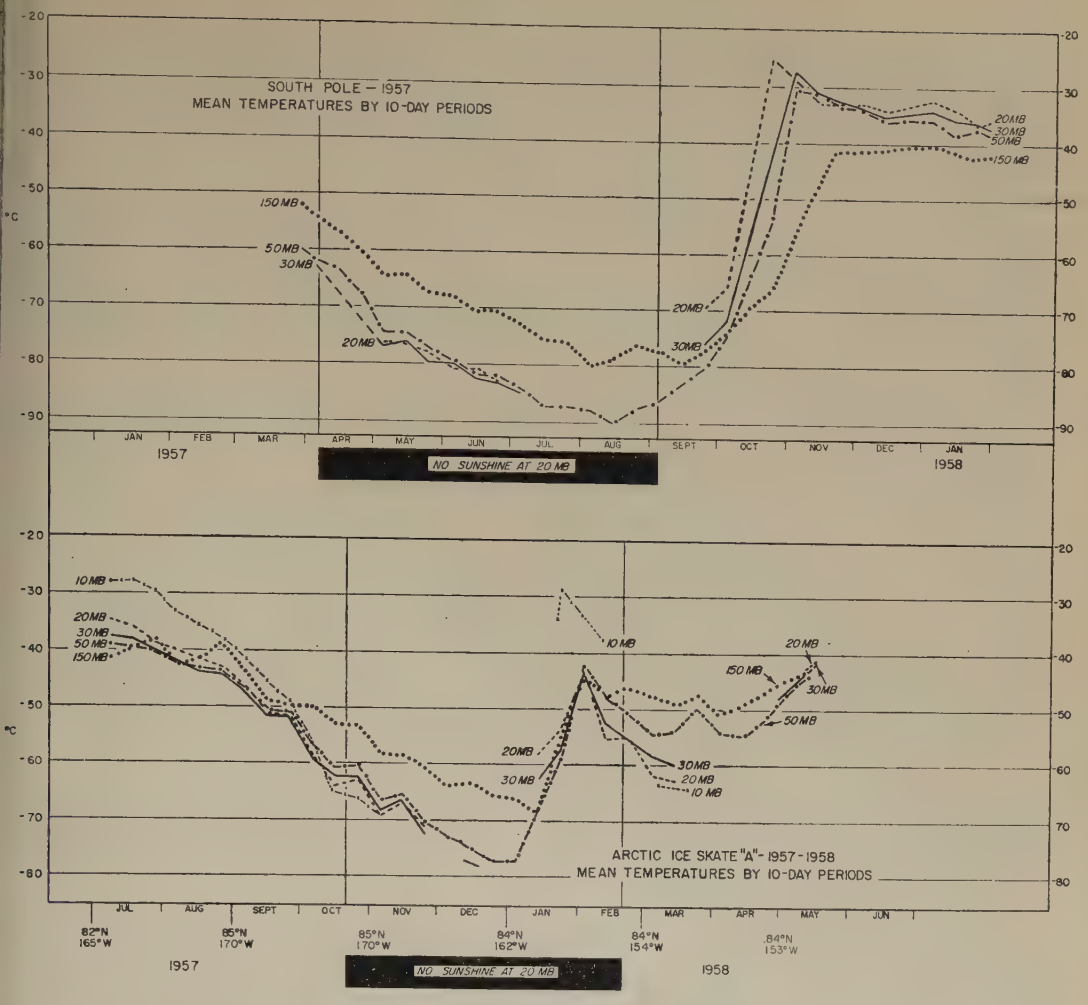

Figure 15. Time-sections of stratospheric temperatures, South Pole and Arctic Ice Station 'Alpha.'

6. Stratospheric cooling and warming

The locations during the I.G.Y. of meteorological stations capable of sounding the atmosphere to great heights at or near the North and South geographic Poles permit a unique examination of seasonal temperature changes in the stratosphere. Fig. 15 shows summarized 1957 and 1958 stratospheric temperature data from the U.S.-I.G.Y. Amundsen-Scott Station at 90°S and Ice Station 'Alpha' which during the period examined drifted between 82°N and 85°N.

For both stations successive 10-day average temperatures are plotted for 150 mb, 50 mb, 30 mb, 20 mb, and 10 mb. The data for the higher levels are scarce, especially in the cold season. Each curve is plotted on the same solar time-scale, with a black zone indicating absence of the sun at 20 mb and below at each station.

As described earlier, after the sun sets at the South Pole, the stratospheric temperatures fall quite steadily at a rate of about $\frac{1}{4}$°C per day, with a slightly greater cooling rate at the higher levels, causing a reversal from the strong temperature increase with height in summer to a decrease in winter. The temperature minimum at 50 mb is reached in mid-August while those at 150 mb are in early August and mid-September. A slow temperature rise at 50 mb begins a few weeks before the sun returns but becomes much more marked after early September when the sun's radiation reaches the lower strata. During October

the 50 mb temperature increases nearly 50°C; but the rise at 150 mb is much less marked. The 20-, 30- and 50-mb temperatures show a distinct maximum in late October and early November after which the temperature *declines* irregularly but achieving a slight, secondary maximum at the summer solstice. The strong temperature increase with height after the sun's return, and especially in October, is quite evident.

Turning to the drift station near the North Pole, here again the temperature decreases as the sun departs, but more irregularly than at the South Pole. The cross-over point from stratospheric temperature inversion to lapse occurs as the sun vanishes below the horizon in early October. At this time the temperatures are not much different from those at the South Pole. As cooling proceeds the temperature minimum at 50 mb is reached in early January and at 150 mb in mid-January, both minima, however, were 12°C higher than those at the South Pole.

A marked temperature rise begins at both levels six weeks *before* the sun returns! Both the 50 and 150 mb temperatures rise to a sharp maximum near 1 February, decreasing thereafter, despite the returning sun. The high temperature of − 30°C at 10 mb is particularly worthy of notice, but the temperature maxima are not as high as those at corresponding levels over the South Pole. After a slight drop the 50 and 150 mb temperatures rise, presumably to a maximum at the summer solstice.

There are two especially interesting features of the Antarctic and Arctic stratospheric temperature curves. The first is the strong temperature maximum at the South Pole shortly after the sun returns. The intensity of this temperature rise, averaging nearly 2°C a day in October and the slow decline thereafter despite the more intense solar radiation, point strongly to a significant contribution to heating by dynamic processes resulting in subsidence of air and adiabatic heating. The daily 50-mb synoptic charts analysed by W. B. Moreland at the I.G.Y. Antarctic Weather Central at Little America show that as the intense polar cyclone characteristic of the polar night (see Fig. 6) weakened and moved away from the Pole towards the Weddell Sea, its associated jet stream crossed the Pole in late October at the time of the highest temperature at 20, 30, and 50 mb and was then replaced by an anticyclone (Moreland 1959).

The second noteworthy event was the strong warming near the North Pole several weeks before return of the sun. This particular warming, described by Teweles and Finger (1958), is another example of the ' explosive ' stratospheric warming first noted by Scherhag (1952) from very high-altitude soundings and observed almost each year since. This phenomenon has not been satisfactorily explained, although the evidence against the solar-heating explanation of Scherhag and others has been steadily increasing in favour of dynamic causes associated with baroclinic instability of the polar-night jet (Wexler 1956, Wexler and Moreland 1958). The stratospheric warmings observed in the Arctic and sub-Arctic have all occurred in the period from the winter solstice to the spring equinox, with the latter half of the period favoured. In contrast the main stratospheric warming in Antarctica, admittedly based on a more limited record, appears to occur shortly after the spring equinox*.

In both the Arctic and Antarctic stratospheres it appears that the intense warming is a result of the sudden onset of subsidence associated with changes in the large-scale circulation pattern. Although each of the changes may be caused indirectly by the returning sun the resulting patterns may differ widely : in the Southern Hemisphere, the polar vortex and its jet stream move away from the Polar Plateau and weaken rapidly; in the Northern Hemisphere, the polar vortex breaks down into meandering waves and cut-off vortices similar to the well-known ' blocking ' pattern of the troposphere.

The earlier onset of stratospheric warming in the Arctic is undoutedly related to a greater tendency for release of baroclinic instability of the stratospheric vortex in the Arctic with consequent breakdown of the westerlies into large-scale meanders and cut-off anticyclonic and cyclonic vortices. Just why the stratospheric vortex in the Arctic should be more susceptible to such a breakdown than its counterpart in the Antarctic is rather

* The observations for the 1958 spring followed quite closely the warming pattern of the 1957 spring.

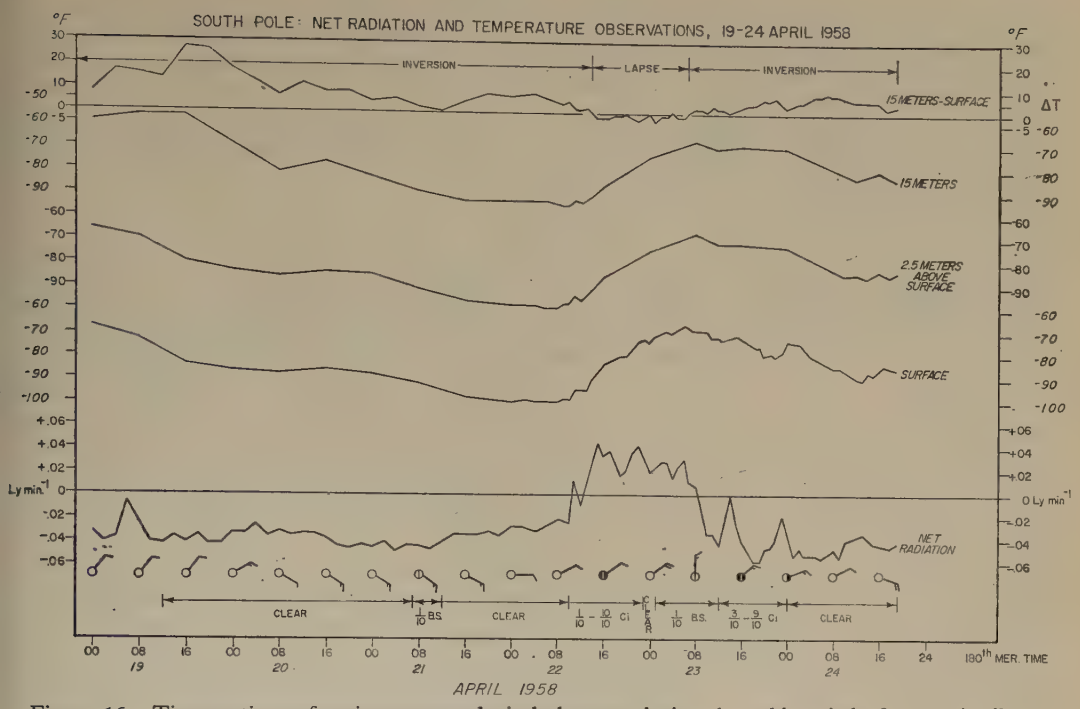

Figure 16. Time-sections of various meteorological elements during the cold period of 19-24 April 1958 at the South Pole.

puzzling. It may well be that in contrast to the Southern Hemisphere, perturbations introduced by the marked zonal contrasts of land and ocean in the Northern Hemisphere extend high into the stratosphere to initiate the breakdown of the polar vortex.

7. A CASE STUDY OF WARM CLOUD EFFECT ON SURFACE TEMPERATURE

The phenomenon of radiation from a warm cloud increasing the surface temperature is well known (e.g., Ballard 1937). An example at the South Pole was described by Wexler (1958b) without the benefit of net radiation measurements. These observations, thanks to the careful work of Mr. Kirby Hanson and his meteorological staff, were available during the cold period of 19-24 April 1958 and the data are shown in Fig. 16. In addition to the net radiation data (1 ly = 1 cal cm^{-2}), the temperatures for the snow surface, 2·5 m and 15 m above the surface are plotted against time. Also the temperature difference, 15 m minus surface, is plotted as well as cloud cover and type, wind speed and direction. A wind coming from the top of the figure is blowing S along the Greenwich meridian (0° longitude), a wind from the right is blowing S along the 90°E meridian and so on. On the tail of the arrow a half-size feather denotes 5 kt and a full-size feather, 10 kt.

On 19, 20, and 21 April, the skies are clear and winds are light; the net radiation is negative showing a rather constant loss of energy of about 0·04 ly min^{-1}. As a result the temperatures at the surface, 2·5 m and 15 m fall steadily by almost 30°F with the surface reaching nearly — 100°F. Shortly after 08 hr on 22 April, cirrus clouds appear which abruptly reverse the radiative loss into a radiative gain of about the same amount, whereupon the surface, 2·5 m and 15 m temperatures begin to rise and increase by 30°F in 24 hr. Simultaneously the surface inversion of temperature, so strongly present during the first three days, changes into a temperature lapse.

The cloud system varies considerably in coverage and presumably in density (such observations are of course difficult to make during the night and especially when blowing snow (BS) is present). Assuming the cloud is located in the troposphere above the cold-surface layer its temperature would be between — 38°C (top of the inversion) and — 60°C (tropopause), or at least 10° higher than the lowest surface temperature. Since clouds

radiate nearly the full black-body energy at their temperature it is apparent that the colder snow surface must gain energy from the warmer cloud and thus warm up. After the surface temperature changes to a lapse, convection then transports heat to the 2·5 m, 15 m, and even higher levels.

The clouds finally disappear by 00 hr 24 April and net radiation becomes strongly negative again, with the surface, 2·5 m and 15 m temperatures decreasing and the surface inversion of temperature forming once again.

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Mean meridional circulations in the atmosphere

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(Manuscript received 20 March 1958; in revised form 31 January 1959)

SUMMARY

The mean meridional circulation in winter and summer is derived as a function of latitude and height from an analysis of observed winds in the area 160°W-0-40°E, 75°N-15°N. The results confirm the classical idea of a direct circulation in low latitudes, but the indirect circulation in middle latitudes is stronger than expected. An investigation of the energy released by the meridional circulation implies that it is of comparable importance to large-scale disturbances in the energy balance of the general circulation.

1. INTRODUCTION

In an earlier paper (Tucker 1957) the mean meridional velocity at the surface, $\bar{v}$, was derived as a function of latitude. The object of the present paper is to extend that analysis to upper levels and so to obtain the mean meridional circulation as a function of latitude and height.

Previous attempts to determine $\bar{v}\,(p)$ or $\bar{v}\,(z)$, where p and z are the vertical pressure and height coordinates, and the overbar denotes a mean in time and around a latitude circle, have been unsuccessful largely because of the inhomogeneity of the data. The most complete attack on the problem was made by Starr and White (1954b) but a critical examination of their procedure reveals three points which emphasize the difference in approach from the results which will be described below :

(i) The method of Starr and White is based on a simple arithmetic averaging of observed values reasonably close to a specific latitude circle. Because the distribution of upper-air stations is very irregular, this attempt to locate the existence of a flow as delicate as the mean meridional circulation does not meet with success.

(ii) The method of processing the data was based upon complete objectivity, that s, no attempt was made to allow for inhomogeneous observations and each station and level were treated independently.

(iii) No attempt was made to allow for the alarming fall-off in observations at upper levels, particularly in high winds and disturbed weather.

There are grounds therefore for arguing that the estimates of Starr and White are not completely representative, particularly because their surface values of $\bar{v}$ are at variance with estimates based on a more representative selection of data (Riehl and Yeh 1950, Tucker 1957). Accordingly, the following analysis is based upon charts of the field of mean meridional and zonal motion in the Northern Hemisphere drawn from as complete a network of surface stations and upper-air radar stations as possible. These charts were constructed at various standard pressure levels from the surface to 300 mb. Complete longitude coverage was possible for the surface but not for the upper levels. The charts were then used to obtain mean zonal and meridional velocities. Meridional velocity was corrected for the limited longitude field and the mean vertical velocity was derived as a function of latitude and height. Finally, the mean velocities were used to obtain an estimate of the energy released by the mean meridional circulation.

2. DATA

The sparse distribution of regularly observing radar- and radio-wind stations limited the field of investigation to within 15°N-75°N and 160°W-0-40°E. The network of upper-air stations used, radar- and radio-wind (Appendix I) and subsidiary pilot-balloon stations (Appendix II), have been plotted on the Key Chart (Fig. 1). Throughout, the analysis velocities are expressed in metres per second with the sign convention : zonal motion, westerlies positive; meridional motion, southerlies positive.

* Now with the Meteorological Office, Harrow, Middx.

Figure 1. Key Chart. ●, radar- or radio-wind stations. ○, pilot-balloon stations. ⊗ stations for which a comprehensive set of pilot-balloon soundings covering the period of analysis were used. All stations are listed in Appendices I and II. Thickened lines denote the boundary of the area of analysis

(*a*) *Radio- and radar-wind data*

Observations of radar- and radio-winds in a form suitable for the computation of seasonal mean vector winds were available for relatively few stations. Therefore computations were carried out to make a reasonable network using the U.S. Weather Bureau publication *Daily Series Synoptic Weather Maps* in which daily observations at 0300 GMT at all reporting radio- and radar-wind stations in the Northern Hemisphere are tabulated. Many missing observations were provided by the Meteorological Services of France, Iceland and Italy. Infrequent reports from the U.S.S.R. and large blank areas in the Pacific set the 40°E and 160°W boundaries to the field of study, and a paucity of observing stations in very low and very high latitudes set the 15°N and 75°N boundaries. Because of the large number of pilot balloons lost in cloud, the radar- or radio-winds were the primary source of data.

The levels of analysis were determined by the tabulation of observations in the *Daily Series Synoptic Weather Maps* at 850, 700, 500 and 300 mb. The next level reported was 200 mb, but although it was desirable to use this (presumably) important level, the number of observations reaching it did not warrant the vertical extension of the analysis. A two-year period of observation was chosen for the computation of mean winds October 1949 to September 1951 inclusive; the later data were determined by the latest data available at the time of computation.

The minimum number of observations in one month necessary for the average to be considered significant was arbitrarily assumed to be 20. If the number of observations at a certain level in one month fell below 20 then it was assumed that the overall ratio between the components at that level and the one below was the same as the ratio computed from only the observations which reached the upper level. Mean monthly values of both meridional and zonal velocity components were computed to the nearest 0·1 kt and converted into m sec^{-1} – the standard unit of the analysis. Equal weight was given to each monthly mean when deriving seasonal values.

Because of the sparsity of reports from Honolulu and Fort Randall (Aleutian Islands), composite values were created by compounding observations from the nearby stations of Hilo and St. Paul Is. respectively.

(*b*) *Pilot-balloon data*

The 140 pilot-balloon stations used are inhomogeneous as regards the period of observation; they are used only as subsidiary data supplementing the radar- and radio-wind observations. Because of loss of balloons in cloud the arbitrary procedure was adopted of using pilot-balloon resultant winds up to the level reached by 50 per cent of the balloons released from the surface.

Mean seasonal resultant winds were computed from German radar-wind data (obtained during World War II) but because of uncertainties in the period of observation and accuracy these are only considered as reliable as pilot balloons.

Sources of data are listed in the bibliography (Appendix II).

(*c*) *Charts*

The two seasons considered are the Northern Hemisphere winter (December, January and February) and summer (June, July and August). Seasonal meridional and zonal velocity components (v and u) were computed for each station at each level of analysis. Data were entered on Northern Hemisphere circumpolar charts and smooth isopleths of v and u were drawn. Each chart was constructed with reference to the level below but without reference to fields of pressure or contour height. Mean components for 5-degree latitude belts were then calculated for each level.

(*d*) *Accuracy of results*

Detailed assessments of the accuracy of the mean velocity components computed from the charts have been made elsewhere (Tucker 1954); these are outlined below.

Charts of the standard vector deviation of upper winds (Brooks *et al.* 1950) were used to estimate the standard deviation of the velocity components, σ, in each 5-degree square, assuming a normal circular distribution of vector deviation about the resultant wind. The standard deviation of the mean component along the latitude belt, σ_ϕ, was taken to be the root mean square of σ in the belt. An estimate was made of the number of observations, N_ϕ, upon which each mean value was based. The standard error, Σ_ϕ, of the mean component in each latitude belt is then given by

$$\Sigma_\phi = \frac{2\sigma_\phi}{\sqrt{N_\phi}}$$

where the arbitrary factor of 2 is inserted to allow for a possible serial correlation of daily observations, assumed to be very small by the fourth day. The values of Σ_ϕ to the nearest 0·05 m sec^{-1} are given in Table 1.

TABLE 1. THE STANDARD ERROR (Σ_ϕ) OF MEAN VELOCITY COMPONENTS (m sec^{-1})

	Latitude (°N)	65-60	55-50	45-40	35-30	25-20	15-10	5-0
	Level (mb)							
Winter	Surface	0·20	0·15	0·15	0·10	0·10	0·05	0·05
	850	0·20	0·15	0·15	0·15	0·10		
	700	0·20	0·25	0·20	0·15	0·15		
	500	0·30	0·30	0·30	0·25	0·25		
	300	0·40	0·45	0·45	0·40	0·40		
Summer	Surface	0·15	0·10	0·10	0·10	0·05	0·05	0·05
	850	0·15	0·10	0·10	0·10	0·10		
	700	0·15	0·15	0·15	0·10	0·10		
	500	0·25	0·20	0·20	0·15	0·15		
	300	0·45	0·35	0·30	0·30	0·30		

3. CIRCULATION AND DIVERGENCE NEAR THE SURFACE IN THE SECTOR 160°W-0-40°E

The analysis of surface observations in the sector 160°W-0-40°E was compared with that over the whole hemisphere with a view to establishing the extent to which the sector may be regarded as representing hemispheric conditions near the surface.

(*a*) *Velocity components*

The profiles of $\bar{v}(\phi)$ and $\bar{u}(\phi)$, obtained by averaging v and u along 5-degree belts of latitude, are presented in Fig. 2. They tend to overestimate the hemispheric picture.

(i) Meridional profiles. The winter profile is very similar to that for the hemisphere, but the northerly flow across the high-pressure ridge beteen 30°N and 45°N is not as well developed. In summer however this flow is overestimated and the entire belt of northerlies is much greater in width and magnitude than in the hemispheric average.

(ii) Zonal profiles. These curves are also of the same form as for the whole hemisphere but the maxima are overestimated, especially in summer.

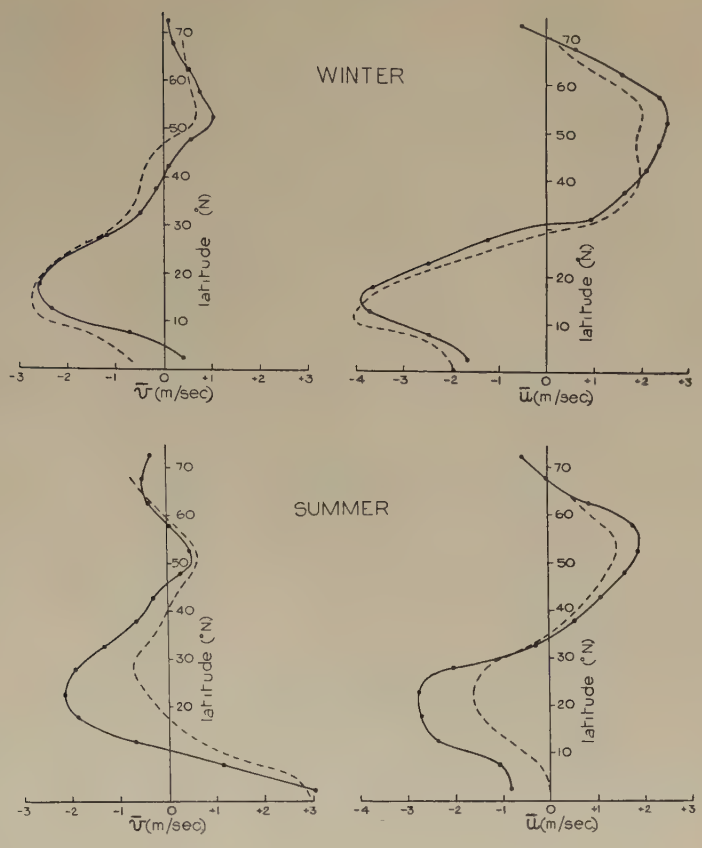

Figure 2. Mean velocity components near the surface in the sector 160°W–0–40°E. Dotted lines denote the profiles for the hemisphere (Tucker 1957).

(*b*) *Mean divergence*

Profiles of mean divergence given in Fig. 3 were computed from the formula

$$\mathrm{div}_2 V \equiv \mathrm{div}\,\bar{v} = \frac{\partial \bar{v}}{r\partial\phi} - \frac{\bar{v}}{r}\tan\phi \quad . \quad . \quad . \quad (1)$$

where $\mathrm{div}_2 V$ is the horizontal velocity divergence, ϕ the latitude and r the radius of the earth (latitude steps of 5 degrees were used in the computations). Compared with the hemispheric profiles they are very similar except for the overestimation of both the southern part of the divergence belt and the low-latitude convergence belt in summer.

The mean surface profiles in the 160°W-0-40°E sector therefore reproduce the main features of the hemispheric profiles, especially in winter, but tend to overestimate in summer.

4. The mean meridional circulation

(*a*) *Meridional component*

As described in § 2 the average meridional component, $\bar{v}$, along the 200-degree latitude arc was obtained for belts of 5-degree width at each level of analysis. Profiles of $\bar{v}$ as a function of pressure-height, p, were drawn for each belt. Because observations only extended to 300 mb, an arbitrary method of extrapolating these profiles to $p = 0$ was devised.

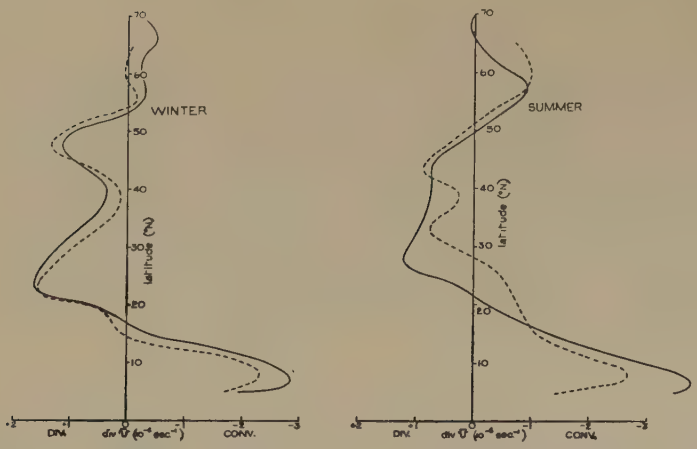

Figure 3. Mean velocity divergence near the surface in the sector 160°W–0–40°E. Dotted lines denote the profiles for the hemisphere (Tucker 1957).

(i) Profiles of $\overline{v}(p)$ were extrapolated by eye to a significant level defined in (ii)

(ii) The significant level was assumed to vary linearly with latitude from 250 mb at 70°N to 100 mb at 10°N

(iii) Above this level the meridional component was assumed to decrease linearly with pressure to $\overline{v} = 0$ at $p = 0$.

A correction for the mass flow across the 200-degree latitude arc was applied. The integrated mass flux across a latitude circle is given by

$$\int_0^{p_0} \overline{v}\, dp = 0 \qquad . \quad . \quad . \quad . \quad (2)$$

where p_0 is the pressure at the surface (assumed in this analysis to be 1,000 mb). This relation is not necessarily true for a 200-degree latitude arc. Priestley (1951) when meeting this problem adjusted his velocities ' by subtracting a *constant* value from the figures while retaining the condition that $\overline{v}$ tends to zero with p and is about 100 cm sec^{-1} at 1,000 mb.' A similar method would be to subtract $\Delta\overline{v}$ from values of $\overline{v}$ where

$$\Delta\overline{v} = \frac{1}{p_0}\int_0^{p_0} \overline{v}\, dp \qquad . \quad . \quad . \quad . \quad (3)$$

Although not true for a single station this seems a reasonable procedure regarding a 200-degree latitude arc, therefore the non-zero effect was eliminated by applying the $\Delta\overline{v}$ correction. The integral $\int_0^{p_0} \overline{v}\, dp$ was calculated for each latitude and the corresponding values of $\Delta\overline{v}$ necessary to satisfy Eq. (2) are given in Table 2. $\Delta\overline{v}$ does not exceed 0·3 m sec^{-1}. In the remainder of the paper $\overline{v}$ will refer to the corrected values.

TABLE 2. $\Delta\overline{v}$, THE CORRECTION TO BE SUBTRACTED FROM $\overline{v}$ TO SATISFY THE EQUATION $\int_0^{p_0} \overline{v}\, dp = 0$ (m sec^{-1})

Latitude (°N)	75-70	70-65	65-60	60-55	55-50	50-45	
Winter	+ 0·22	+ 0·19	+ 0·29	+ 0·29	− 0·03	− 0·09	
Summer	+ 0·34	− 0·01	+ 0·08	+ 0·01	− 0·12	− 0·06	
Latitude (°N)	45-40	40-35	35-30	30-25	25-20	20-15	15-10
Winter	− 0·12	− 0·18	− 0·12	− 0·07	− 0·14	− 0·11	− 0·04
Summer	0	+ 0·07	+ 0·08	+ 0·09	− 0·07	− 0·01	+ 0·12

The corrected mean meridional velocities are presented in Fig. 4. The ordinate is pressure, and latitude is plotted on a cosine scale.

Winter (*Fig. 4a*). In low latitudes, strong northerlies at low levels (over 2 m sec^{-1} near the surface) and southerlies aloft (0·8 m sec^{-1} at 200 mb) indicate the existence of a strong direct circulation. North of 35°N a weaker indirect circulation extends to 55°N. Conclusions drawn on the basis of surface data (Riehl and Yeh 1950, Tucker 1957) are therefore verified.

There is also a high-latitude direct circulation which is not evident from surface values; however, the high-level flow north of latitude 50°N is associated with large values of the standard error (Table 1).

Summer (*Fig. 4b*). The whole system has been displaced some 5-10°N but has undergone only minor structural changes. A certain symmetry is revealed about 25°N which is the centre of the direct cell. The indirect mid-latitude circulation is again present, but is weaker than in winter.

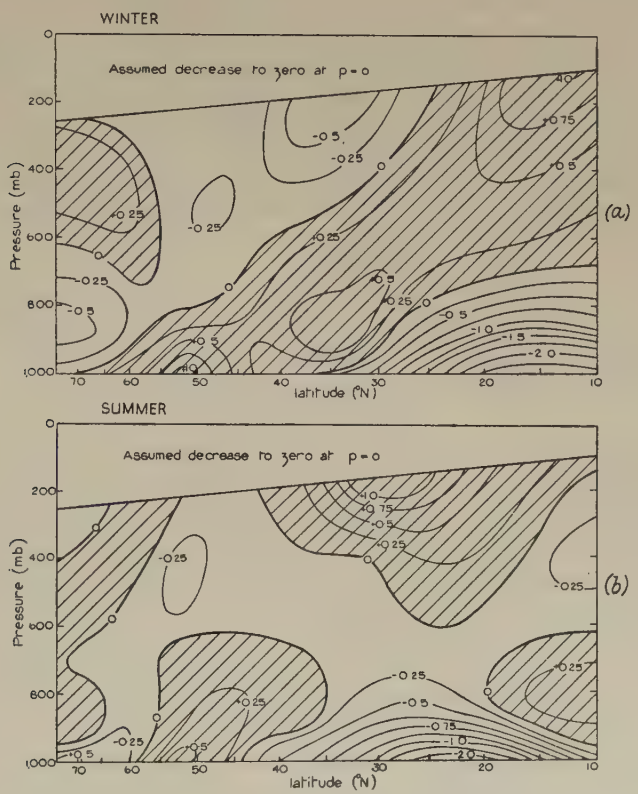

Figure 4. Mean meridional velocity (m sec^{-1}; southerlies shaded).

(*b*) *Vertical component*

The vertical velocities are derived from values of the mean horizontal velocity divergence. Divergences are calculated from finite differences of the mean meridional velocity profile $\bar{v}\,(\phi)$. Eq. 1 was used to compute values of div $\bar{v}$ at each level. (The error involved because mean isobars are not horizontal is negligible). Vertical profiles of div $\bar{v}\,(p)$ were drawn for each latitude (Fig. 5).

The mean surface pressure along a latitude circle was found to vary little between the beginning and end of the winter and summer seasons, therefore the equation of continuity again provides a constraint in the form

$$\int_0^{p_0} \operatorname{div} \bar{v}\, dp = 0 \qquad . \quad . \quad . \quad . \quad (4)$$

In the case of only 3 out of the 120 values of div $\bar{v}$ were adjustments necessary to satisfy Eq. 4.

The vertical axes of the divergence profiles were next changed from pressure to height and the mean vertical velocity at each level was evaluated using the equation

$$\bar{w} = \frac{1}{\rho_z} \int_0^z \rho \operatorname{div} \bar{v}\, dz \qquad . \quad . \quad . \quad . \quad (5)$$

where ρ_z is the density at the level considered. The derived vertical velocities are given in Fig. 6.

Winter (*Fig. 6a*). Latitude 17°N is clearly the dividing line between the ascending and descending branches of the direct circulation. The descending motion occurs in a broad belt (17°N-37°N), attaining a maximum of nearly 10^{-2} m sec^{-1} (25°N, 200 mb). Isopleths cannot be extended above 200 mb with any confidence. The latitudes separating this downward motion from the upward motion to the north and south vary little with height. The zone of ascent 37°N to 47°N does not extend to the surface; this suggests a relation between the indirect cell and some high-level process in the atmosphere. A rapid changeover at 200 mb from $+ 5 \times 10^{-3}$ m sec^{-1} at 45°N to $- 2 \times 10^{-3}$ m sec^{-1} at 50°N occurs at the mean latitude of the polar jet stream. The upward velocities north of 60°N are not very reliable but conform to the idea of a direct circulation in very high latitudes with descending motion in the troposphere over the north pole.

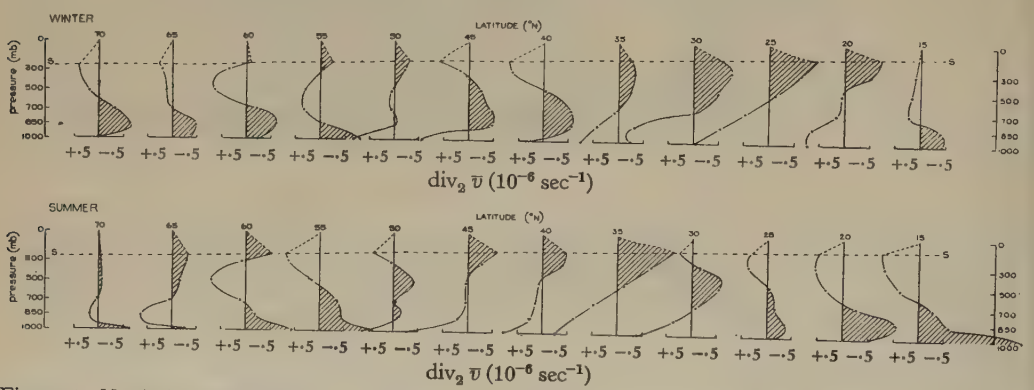

Figure 5. Vertical profiles of mean divergence. The line S S′ denotes the level above which the divergence is assumed to decrease to zero linearly with pressure. Areas of convergence are shaded. The continuity requirement for this figure is $\int_{1,000}^{0} \operatorname{div} \bar{v}\, dp = 0$.

Summer (*Fig. 6b*). The pattern is similar to winter but has been displaced about ten degrees north. Most of the ascending branch of the low-latitude direct circulation is represented, reaching a maximum of 5×10^{-3} m sec^{-1} (20°N, 200 mb). Figure 6b shows that the downward motion between 27°N and 51°N has a maximum at about 36°N and also a secondary maximum at 45°N; this secondary maximum may be associated with the southern descending branch of the indirect circulation (c.f. § 4 (a)).

(*c*) *Mean trajectories*

The diagrams of $\bar{v}$ (ϕ, p) (Fig. 4) and $\bar{w}$ (ϕ, p) (Fig. 6) were used to plot the paths of four particles, A, B, C, D, each initially at a height of 10 km and at latitudes 60, 50, 40 and 20°N respectively (Fig. 7). Time steps of 10 days ($8{\cdot}6 \times 10^5$ sec) were used and the resulting trajectories are plotted on a linear height scale. These trajectories are obviously artificial because they refer to a mean flow pattern assumed constant in time; nevertheless they reveal certain interesting features.

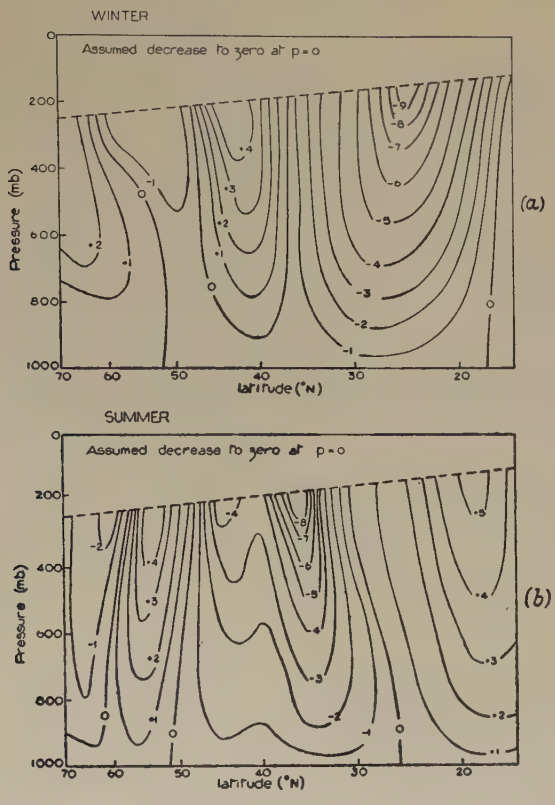

Figure 6. Mean vertical velocity in winter and summer (10^{-1} cm/sec, ascending motion positive).

Winter (*Fig. 7a*). The direct circulation of the tropics is manifest in the path of D which completes a circuit in about 80 days, experiencing horizontal and vertical displacements of amplitude 30 degrees (3,300 km) and 10 km respectively. The indirect cell is indicated by the path of C with amplitudes of 15 degrees and 10 km in about 120 days. The path of A suggests the extension northwards of the indirect cell in the lower layers as a very slow circulation. The path of B, linked with the upper portions of A and C, suggests a high-level direct circulation north of the polar front jet stream but the reliability of the deduction is open to question.

The whole pattern depicted by Figure 7a can be compared with the scheme suggested by Palmén (1951) for the Northern Hemisphere (Fig. 8). The tropical cell exists in the same size, form and position. North of this the indirect circulation between the polar

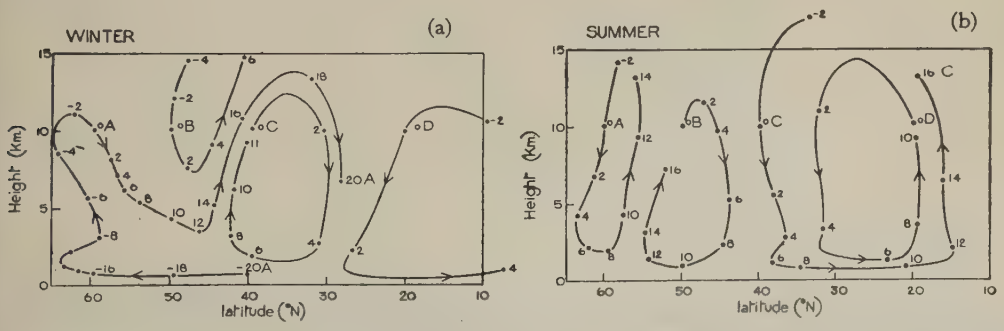

Figure 7. Mean trajectories in winter and summer. The figures indicate the time (× 10 days) since the particles were at their initial position.

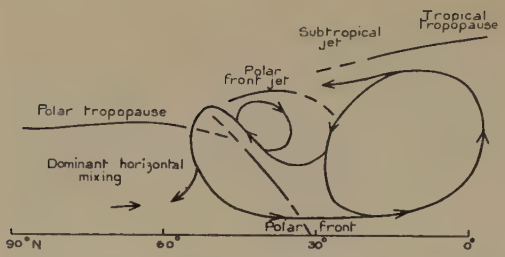

Figure 8. Scheme of mean meridional motion in winter suggested by Palmén (1951).

front and subtropical jets appears to be more significant than Palmén suggests and extends to the surface. The direct circulation north of the polar jet suggested by the path of B is confined to the upper troposphere, but the downward motion between 50°N and 60°N suggested by Palmén is substantiated by the downward motion of A (− 2 to 8) and B (− 4 to 2).

Summer (*Fig. 7b*). These trajectories show up clearly the three circulations suggested by the vertical velocities. The importance of the direct cell is indicated by the amplitude and period of the orbits of C and D.

(*d*) *Comparison with other estimates*

Several estimates of the mean meridional velocity at specific latitudes have been made in recent years (Priestley 1949, Starr and White 1952 a and b, 1954 a and b, Buch 1954, Mintz and Lang 1955, Palmén *et al.* 1957). These involve various methods, and in some cases only values for the whole year are published. A comparison of estimates published for winter and summer seasons has been made in Fig. 9.

The method of Mintz and Lang involves an assumption that the vertical eddy flux of momentum vanishes above 700 mb. This is probably a serious error (Sheppard 1954). All their values of $\bar{v}$ at 30°N are less than 0·11 m sec^{-1}.

The approach of Buch was similar to that employed here; however, he, as well as Starr and White, used observations of winds at very high levels where a large proportion of balloons were lost. This may account for the discrepancy between these estimates at high levels, but taking account of this, the agreement between the winter profiles elsewhere is reasonable. In summer the differences are quite large; if however Buch had used surface observations to extend his values to the lowest levels the agreement below 400 mb would be reasonable. The main criticism of both Starr and White and Buch is that their curves do not satisfy the continuity requirement $\int_0^{p_0} \bar{v}\, dp = 0$.

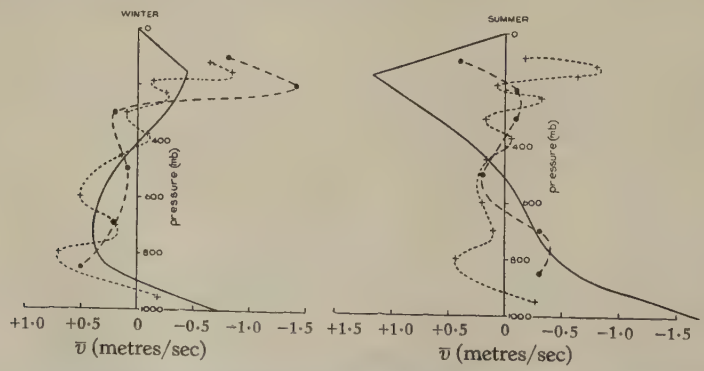

Figure 9. Comparison of estimates of the mean meridional circulation at 30°N. Present analysis (full line); Buch 1954 (● – – – – ●); Starr and White 1952 (+ – – – – +).

5. Energy release

It is obvious that in order to maintain the kinetic energy of large-scale motion against the dissipative effects of friction there must be a utilization of potential and thermal energy which are in turn replenished by solar radiation. One of the main problems in meteorology remains the satisfactory explanation of the mechanism of this energy transformation and of the organization of kinetic energy to produce and maintain the observed flow pattern. The existence of mean meridional circulations is of some importance in this problem because, if in completing the cycle, the path of a particle encloses a number of isobaric-isosteric solenoids, work must be done on or by the atmosphere according to the sense of the motion. The mean trajectories of Fig. 7 enable a somewhat crude estimate to be made of the energy released by plotting the paths of selected particles of air on a thermodynamic diagram (the tephigram). The results are little better than an order of magnitude but can be compared in reliability with estimates by other workers of the energy dissipated by friction.

The temperature field is considered steady and at the end of each cycle the particle returns to its original temperature and pressure. Since there is no change in the internal or potential energy of the system, all the energy liberated is converted into kinetic energy, the amount of energy depending largely on the horizontal and vertical amplitude of the displacement. Analysing these steady-state mean circulations in this manner implicitly assumes that the condensation and precipitation of water from each particle during ascent is returned to it by evaporation by the time it regains its original position. The mean field of virtual temperature was not available, therefore a dry atmosphere is considered by using the mean meridional temperature cross-sections presented by Petterssen (1950).

Three meridional systems are evident in both winter and summer, the low latitude, mid-latitude and the less reliable high-latitude circulations. Estimates of the vertical and horizontal extent of these circulations are given in Table 3, together with the total mass involved. The arbitrary upper boundary, 100 mb, assumed for most of the tropospheric circulations, allows for the possibility of a stratospheric circulation.

TABLE 3. Dimensions of the mean meridional cells

Circulation	Vertical extent (mb)	Latitude extent	Mass (10^{20} g)
Winter			
Low latitude	1,000-(100)	27°N-10°S	15
Mid latitude	1,000-(100)	42°N-27°N	9
High latitude	500-(100)	52°N-42°N	1
Summer			
Low latitude	1,000-(100)	43°N-10°N	14
Mid latitude	1,000-(200)	53°N-43°N	2
High latitude	1,000-(100)	63°N-53°N	2

(Brackets imply interpolated limits)

The paths of each particle in Fig. 7 were traced on the tephigram (temperature against entropy) and are presented in Fig. 10. The path of the most northerly particle, A, has been omitted as it proved relatively unimportant. The energy released per unit mass for each cycle is given by the area enclosed by the curves and the rate of release is tabulated in Table 4.

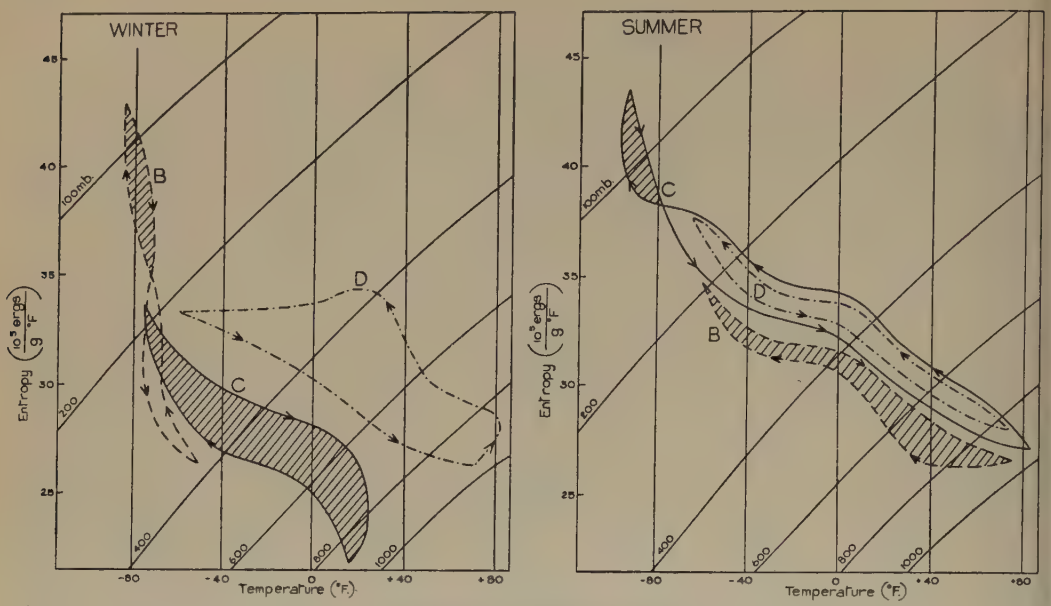

Figure 10. Trajectories plotted on the tephigram of particles involved in mean meridional circulations. These particles are plotted in space in Fig. 8. Indirect circulations are shaded.

TABLE 4. RATE OF ENERGY RELEASE PER UNIT MASS (e) FOR EACH CYCLE (suffixes refer to the particle concerned)
Unit 10^{-2} joule g^{-1} day^{-1}

	e_A	e_B	e_C	e_D
Winter	0	0	− 3·1	+ 7·9
Summer	+ 0·5	− 1·2	+ 1·7	+ 1·3

Each particle has been regarded as typical of the cell of which it is part, and the rate of energy per unit mass released is a measure of the mean for the entire cell. This assumption is justified since the path in the outer region of the circulation cell embraces more solenoids than does one nearer the centre, but takes a longer time. For example, the path of C in summer amounts to 2·8 joule g^{-1} in 170 days whereas D amounts to 1·3 joule g^{-1} in 100 days. Estimates of the mean rate of energy released per unit mass are given in the first column of Table 5. The rest of Table 5 presents the total rate of energy released by each cell and the overall rate of release (the sum of the three cells) by the mean meridional circulation in the Northern Hemisphere.

TABLE 5. RATE OF ENERGY RELEASE DUE TO MEAN MERIDIONAL CIRCULATION

Circulation cell	Rate of energy release per unit mass (e) 10^{-2} joule g^{-1} day^{-1}		Mass involved (m) 10^{20} g	Rate of total energy release (em) 10^{18} joule day^{-1}	Overall rate of energy release 10^{18} joule day^{-1} (10^{27} erg day^{-1})
Winter					
Low latitude	e_D	+ 8	15	+ 120	
Mid latitude	e_C	− 3	9	− 27	+ 93 (+ 0·9)
High latitude	e_B	0	1	0	
Summer					
Low latitude	$\frac{1}{2}(e_C + e_D)$	+ 1·5	14	+ 21	
Mid latitude	e_B	− 1	2	− 2	+ 19 (+ 0·2)
High latitude	e_A	+ 0·5	2	+ 1	

Brunt (1926) has estimated, from the rate of dissipation of kinetic energy, that the energy required to maintain the general circulation is about 2×10^{27} erg day^{-1} for both hemispheres. If we assumed the energy released by Southern Hemisphere mean meridional circulations to be about the same as in the Northern Hemisphere, the figure computed for the combined winter and summer hemispheres is $1{\cdot}1 \times 10^{27}$ erg day^{-1}. In view of the very large tolerance which must be afforded to each estimate their proximity is encouraging and leads to the conclusion that mean meridional circulations and large-scale disturbances are of comparable importance in the energy balance of the general circulation.

6. Conclusions

The increased number of upper-air wind observations since World War II has made it possible to detect the mean meridional circulation in the Northern Hemisphere with a reasonable degree of accuracy. The Asiatic longitudes could not be included in the analysis and the omission of the winter sub-tropical jet over Southern Asia and the jet stream near Japan probably distorts the derived winter scheme. However, both winter and summer data confirm many of the features in the scheme proposed by Palmén (1951). The low-latitude direct circulation is most important by virtue of its magnitude and extent; however, the middle-latitude indirect circulation proves to be of greater significance than hitherto expected.

The rough estimate of the energy released by the mean meridional circulation shows it to be comparable to the combined effects of smaller scales of atmospheric motion in maintaining the kinetic energy of large-scale motion against the dissipative effects of friction.

Acknowledgments

I should like to thank Professor P. A. Sheppard, who suggested this work, for much helpful criticism. My thanks are also due to the Director-General of the Meteorological Office for permission to use the records at the World Climatology Branch, and to the Directors of the following meteorological services for data provided : Canada, France, Iceland, Italy, Sudan and U.S.A. During the course of this work I was in receipt of a D.S.I.R. Maintenance Award.

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	1957	*Quart. J. R. Met. Soc.*, **83**, p. 290.

APPENDIX I

Radar- and radio-wind stations

Standard period: Winter 1949-50, 1950-51; Summer 1950, 1951

No.	Name	Position °N	Position °W	No.	Name	Position °N	Position °W
1a	Hilo	20	155	42	Goose	53	60
1b	Honolulu	21	158	43	Mingan	50	66
2	Weather Ship *U*	28	145	44	Stephenville	49	59
3	Weather Ship *N*	33	135	45	Caribou*	46	69
4	Weather Ship *P*	50	145	46	Nantucket*	41	70
5a	Ft. Randal	55	162	47	Weather Ship *H*	36	70
5b	St. Paul Island	57	170	48	Kindley Field	32	65
6	Nome	65	175	49	San Juan*	18	66
7	Barrow	71	157	50	Angmagssalik	66	38
8	Whitehorse	61	135	51	Narssassuaq	61	45
9	Edmonton	54	114	52	Weather Ship *B*	56	51
10	Prince George	54	122	53	Weather Ship *A*	62	33
11	Tatoosh*	48	125	54	Keflavik	64	23
12	Spokane*	48	118	55	Weather Ship *M*	66	02E
13	Medford*	42	123	56	Weather Ship *I*	59	19W
14	Oakland	38	122	57	Weather Ship *C*	53	35W
15	Santa Maria*	35	120	58	Weather Ship *D*	44	41W
16	Albuquerque*	35	107	59	Weather Ship *E*	35	48W
17	Grand Junction*	39	109	60	Stockholm	59	18W
18	Ft. Smith	60	112	61	Lerwick†	60	01W
19	Bismark*	47	101	62	Aldergrove†	55	06W
20	Rapid City*	44	103	63	Weather Ship *J*	52	20W
21	Big Spring*	32	102	64	Berlin	52	14E
22	Oklahama City*	35	98	65	Munich	48	12E
23	San Antonio*	30	98	66	Larkhill†	51	02W
24	Brownsville	26	97	67	Brest	48	04W
25	Resolute	75	95	68	Weather Ship *K*	45	16W
26	Churchill	59	94	69	Lagens	39	27W
27	International Falls*	48	93	70	Milan	45	09E
28	St. Cloud*	46	94	71	Bordeaux	45	01W
29	Columbia	39	92	72	Athens	38	24E
30	Little Rock*	35	92	73	Rome	42	13E
31	Burrwood*†	29	89	74	Gibraltar†	36	05W
32	Eureka	80	86	75	Maison Blanche	37	03E
33	Sault Ste. Marie*	46	84	76	Malta†	36	14E
34	Nashville*	36	87	77	Benina†	32	20E
35	Thule	77	69	78	Nicosia†	35	33E
36	Clyde River	70	69	79	Farouk	30	31E
37	Frobisher	64	69	80	Habbaniyah†	33	44E
38	Hatteras*	35	76	81	Bahrein†	26	51E
39	Greensboro*	36	80	82	Aden†	13	45E
40	Charleston*	33	80	83	Nairobi†	01S	37E
41	Miami*	26	80	84	Lagos†*	07N	03E

* Data obtained from U.S. Weather Bureau, *Climatological Data, National Summary*, Washington 1950, New Orleans 1951, Ashville 1952. *† One year only, 1950-51 Winter, 1951 Summer. † Data obtained from records in the World Climatology Branch, Meteorological Office, London. †* One year only, 1953.

APPENDIX II

Pilot-balloon stations

The 'period' is a subjective estimate of the approximate number of years from which observations were taken. The reference number of the source of information is given for a more detailed account. An asterisk denotes that pilot-balloon observations were summarized over the exact period of analysis, Winter 1949-50, 1950-51 and Summer 1950, 1951.

No.	Name	Position		Period	No.	Name	Position		Period
1	Uelen	66N	170W	2	51	Port au Prince	19N	72W	8
2	St. Paul Island	57	170	3	52	Maracaibo	11	72	2
3	Dutch Harbour	54	166	3	53	La Guira	10	67	3
4	Barrow	71	157	3	54	St. John Island	17	62	5
5	Fairbanks	65	148	8	55	Port of Spain	11	61	3
6	Anchorage	61	150	3	56	Georgetown	07	58	3
7	Aklavik	68	135	3	57	Cayenne	05	52	3
8	Juneau	58	135	6	58	Keflavik	64	22	18
9	Vancouver	49	123	2	59	Archangel	65	40E	1
10	Grand Forks	49	119	1	60	G.R.W.1	70	25	—
11	Fort Simpson	62	121	2	61	Sodankyla	67	27	2*
12	Coppermine	68	115	1	62	Ilmala (Helsinki)	60	25	2*
13	Chesterfield Inlet	63	91	5	63	Sluzk	60	31	5
14	Coral Harbour	64	83	3	64	G.R.W.5	59	27	—
15	Etah	70	73	1	65	G.R.W.3	63	09	—
16	Port Harrison	58	78	5	66	Puck	55	18	7
17	Toronto	44	80	10	67	Malmo	56	13	7
18	Cape Hope's Advance	61	70	1	68	G.R.W.9	63	09	—
19	Fort Chemio	58	68	2	69	G.R.W.10	54	18	—
20	Belle Island	53	55	4	70	Warsaw	52	21	5
21	Cape Race	47	54	2	71	Wilmo	55	25	5
22	St. Paul Island (N.S.)	47	60	3	72	G.R.W.7	50	34	—
23	Fame Point	49	65	4	73	Vienna G.R.W.18	48	17	—
24	Sable Island	44	60	3	74	De Bilt	51	05	2*
25	St. John's Radio Station	45	66	3	75	G.R.W.4	50	05	—
26	San Diego	33	117	7	76	G.R.W. (Kastanza)	38	23	—
27	El Paso	32	106	7	77	G.R.W.32	37	29	—
28	Hermonsillo	29	111	3	78	G.R.W.30	38	23	—
29	Del Rio	29	101	7	79	Valona	40	19	3
30	Torreon	25	103	3	80	G.R.W.31	37	15	—
31	Mazatlan	23	106	8	81	Palermo	38	13	5
32	Tampico	22	98	11	82	Zara	44	15	5
33	Mexico City	19	99	6	83	Maddalena	41	09	5
34	Vera Cruz	18	96	11	84	G.R.W.20	44	10	—
35	Tehuantepec	17	95	11	85	Marseilles	43	05	7
36	Tapachula	15	93	7	86	G.R.W.24	40	03	—
37	Merida	21	89	7	87	Barcelona	41	02	8
38	San Salvador	13	89	2	88	Alicante	38	00	10
39	Managua	13	86	2	89	Corunna	43	08W	4
40	San Julian	22	84	3	90	San Antiocco	39	08	5
41	Swan Island	17	84	5	91	Tunis	37	10E	7
42	Key West	25	82	18	92	Touggourt	33	06	4
43	David	09	83	6	93	Algiers	37	03	7
44	Albrook Field	10	80	6	94	Oran	36	01W	7
45	Cristobal	09	80	6	95	Colomb Bechar	32	02	7
46	Nassau	25	77	2*	96	Rabat	34	07	9
47	Nuevitos	21	77	3	97	Marrakesh	32	08	7
48	Kingston	18	77	18	98	Agadir	31	10	9
49	Barranquilla	11	75	4	99	Horta	39	29	8
50	Turbo	08	77	1	100	Teneriffe	28	17	10

No.	Name	Position		Period	No.	Name	Position		Period
101	Fort Saint	30N	10E	3	121	Maiduguri	12N	13E	2
102	Fort Flatters	28	07	4	122	Fayid	30	32	5
103	Ouallen	25	01	4	123	Cairo	30	31	5
104	Adrar	27	00	6	124	Alexandria	31	30	5
105	Ocean Square	35-40N	09-19W	7	125	Salloum	32	25	5
106	Ocean Square	30-35	10-20	7	126	Kufra	24	23	5
107	Ocean Square	25-30	10-25	7	127	Asynt	27	31	5
108	Ocean Square	20-25	15-25	7	128	Asswan	24	33	5
109	Ocean Square	15-20	15-25	7	129	Wadi Halfa	22	31	1
110	Ocean Square	10-15	15-25	7	130	Khartoum	16	32	2*
111	Ocean Square	05-10N	10-25E	4	131	Galu	03	32	1
112	Port Etienne	21N	17E	3	132	Kilolo Hill	00	33	1
113	Dakar	15	17	3	133	Bahrdar	12	37	1
114	Konakry	10	14	3	134	Kamaran Island	15	43	5
115	Abidjan	05	04	3	135	Berbera	10	45	1
116	Bamako	13	08	3	136	Bender Cassim	11	49	1
117	Niamey	13	02	3	137	Cape Guardafui	12	51	3
118	Kadura	11	07	1	138	Riyan	15	49	3
119	Kano	13	09	3	139	Salalah	17	54	2
120	Zinder	14	09	3	140	Masirah	21	59	1

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An experimental system for directly recording statistics of the intensity of atmospheric turbulence

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SUMMARY

It is demonstrated theoretically that the 'filtering' effects exerted on a turbulence record by taking averages over an interval s, for a total sampling time τ, may be reproduced by simple electrical filters as far as the variance is concerned. The smoothed rectified output of such a filter may be recorded on a slowly moving chart and, with the further assumption of Gaussian distribution in the amplitudes of the fluctuations, may be read directly as a statistical mean of the standard deviation.

A description is given of an experimental system, and of direct tests of its performance in recording the standard deviation of wind-direction fluctuations when averaged over 5 sec and sampled over 3 min. Proposed applications are briefly outlined.

1. INTRODUCTION

A measure of the intensity of turbulence, as represented by the standard deviation of the time-variation of a component of the motion, is an essential part of any statistical description of the flow, and recent studies of atmospheric diffusion by Cramer (1957) and Hay and Pasquill (1958) are movements in the direction of using this parameter more directly and widely than hitherto in diffusion problems. The latter study contains an empirical adaptation of basic statistical treatments by Taylor (1921) and Batchelor (1949), and provides a very simple formula for the turbulent spread from a fixed continuous source. In this formula the spread is determined by the intensity of the appropriate component, derived from serial values which are averages over a time s and are observed or 'sampled' over a prescribed length of time τ. Referring to Fig. 1 the quantity required is the standard deviation of V_s over the period τ, where s is related in a specified way to the distance from the source, and τ is the time over which the source is released or over which the cloud spread is required, whichever is the smaller.

The significance of associating the standard deviation with particular values of s and τ arises from the fact that the typical turbulence record may be regarded as a composition of a whole spectrum of oscillations covering a frequency range which, especially in atmospheric turbulence, may be very wide. Hence an increase in τ means that the amplitudes of more of the low-frequency oscillations are contained in the derived intensity, while an increase of s means that high-frequency oscillations are more effectively smoothed out. The basic fact that the intensity of atmospheric turbulence varies with sampling time has been known for a long time (see Sutton 1953, p. 249), but it is only recently that the details of the variation have received attention, as part of the increasing tendency to describe turbulence in terms of a spectrum. It is indeed evident that the dependence of the intensity on both 'sampling' and 'averaging' times will reflect the broad features of the shape of the spectrum of turbulent energy.

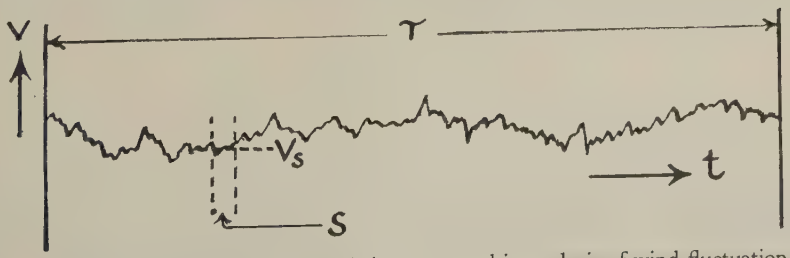

Figure 1. Sampling time τ and 'averaging' time s as used in analysis of wind-fluctuation record.

With the appearance of particular and general applications such as those mentioned above, the measurement and statistical description of intensity of turbulence as a function of ' sampling ' and ' averaging ' times assumes considerable importance. In the first stage of the instrumental problem, that is, in the provision of adequate ' sensing ' devices for measuring the time-variation of the turbulent component, there is no great obstacle to progress. There is, however, an important practical problem involved in the reduction of the basic information to the required form. So far in atmospheric studies the reduction has usually involved extracting values of V_s from a time-lapse record, either visually or by some manual or automatic scanning arrangement, and obtaining the standard deviations by desk or automatic computing machines.

If comprehensive statistics are required it is clear that the labour or cost of the traditional process is likely to be considerable, apart from which there will be the inconvenience of storing the large quantities of records obtained with a relatively high-speed chart. The rest of this paper gives an account of an experimental system which has been developed for directly recording the standard deviation on a slowly moving chart.

2. Electrical reproduction of the mathematical ' filtering ' process

In this section it will be shown that the basic effects of ' sampling ' and ' averaging ' times can be represented easily and automatically by electrical filters. As implied earlier the setting of specific values of τ and s is equivalent to subjecting the whole spectrum of turbulence to a filter which transmits the turbulent energy to a degree which varies with frequency of oscillation n, and this effect may be expressed precisely in terms of n, τ and s. If σ_∞^2 is the variance of a fluctuation observed over effectively infinite time and with infinitesimally small averaging time, and $F(n)$ is the fraction of this variance contained in the frequency range n to $n + dn$ (cycles/unit time), then the variance corresponding to ' sampling ' time τ and ' averaging ' time s is given by

$$\sigma_{\tau,s}^2 = \sigma_\infty^2 \int_0^\infty F(n) \left(1 - \frac{\sin^2 \pi n\tau}{(\pi n\tau)^2}\right) \frac{\sin^2 \pi ns}{(\pi ns)^2}\, dn \qquad . \qquad . \qquad (1)$$

A derivation of the term concerning the effect of ' averaging ' seems first to have been given in the meteorological literature by Batchelor (1949), in his analysis of diffusion of particles, but the form is probably better known through its customary use as a correction factor in power spectrum analysis. A formal derivation of the converse term, representing the effect of sampling time, has been given by Ogura (1957) in a general analysis of the effect of a finite observation interval on the apparent properties of atmospheric turbulence.

Values of the function $1 - \sin^2 \pi n\tau/(\pi n\tau)^2$ are shown graphically in Fig. 2. Apart from the oscillations in the values on the high-frequency side the general shape of the curve is similar to the transmission curve of a ' high-pass ' electrical filter. An examination of filter characteristics was then made and the circuit included in Fig. 3 was ultimately chosen as probably giving adequate representation of the mathematical ' filter ' for most of the purposes in mind. This filter is a conventional two-stage arrangement with the addition of a ' buffer ' valve. If a sinusoidal variation of voltage of amplitude E is applied to this filter, and the output variation has amplitude E', then $(E'/E)^2$, i.e., the ' power transmission ' is theoretically given by

$$\left(1 + \frac{1}{\omega^2 C^2 R^2}\right)^{-2} \qquad . \qquad . \qquad . \qquad . \qquad (2)$$

where $\omega = 2\pi n$, C is the capacity in farads and R the resistance in ohms. This is shown plotted in Fig. 2 against $0{\cdot}44\ n/n'$ where n', the frequency for 50 per cent power transmission, is equal to $0{\cdot}247/CR$. If the overall matching of the two curves is accepted, the output from the filter is thus equivalent to a ' sampling ' time τ equal to $0{\cdot}44/n'$. The points plotted on the graph are confirmatory measurements of filter transmission, which

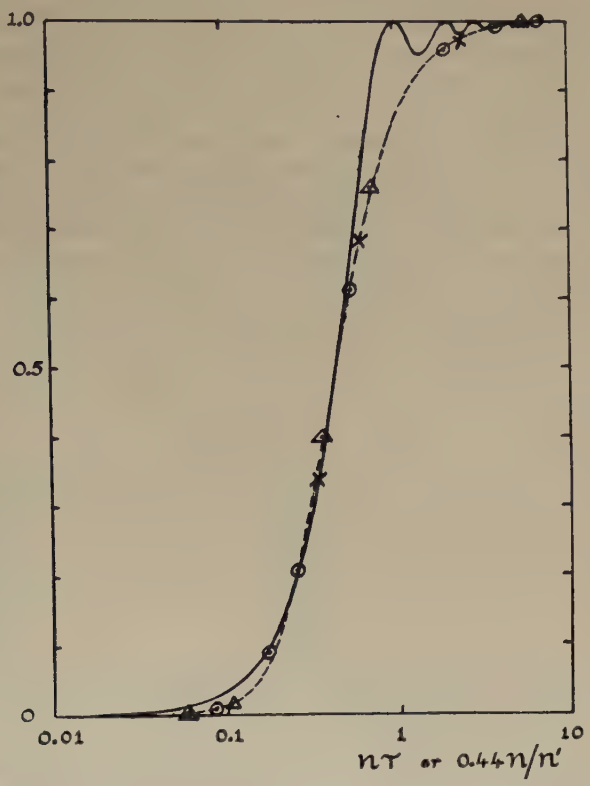

Figure 2. ' Mathematical ' and ' electrical ' filter characteristics.

The ordinates are ——— $1 - \sin^2 \pi n\tau/(\pi n\tau)^2$; – – – – Equation (2).

The points are observed power transmissions for *CR* values (in sec) of 101 (⊙), 16·9 (×) and 2·8 (△).

with certain other practical details are described in a later section. In addition to attenuating the amplitudes of the component fluctuations the electrical filter will also produce phase displacements, but this distortion may be ignored as far as the *variance* of the output is concerned.

The effects of ' averaging ' time may be represented by a ' low-pass ' filter with transmission characteristics approximating to $\sin^2 \pi ns/(\pi ns)^2$, and the combined effects of ' sampling ' and ' averaging ' times could likewise be represented by a ' band-pass ' filter. Alternatively, as in the experimental system considered here, the band-pass effect may be achieved by combining the results of a number of high-pass filters. If these filters correspond to ' sampling ' times τ_1, τ_2, τ_3 (in decreasing order) they will give outputs with variances which we will denote by $\sigma_f^2(\tau_1)$, $\sigma_f^2(\tau_2)$, $\sigma_f^2(\tau_3)$. Provided τ_1, τ_2, τ_3 are sufficiently different among themselves, and provided τ_3 is sufficiently larger than the ' averaging ' time implied by the response characteristics of the ' sensing ' head, the corresponding transmission curves will not significantly overlap. In this case, assuming identity of the curves in Fig. 2,

$$\sigma^2_{\tau,s} = \sigma_f^2(\tau_1) - \sigma_f^2(\tau_2) \quad \text{for} \quad \tau = \tau_1, \quad s = \tau_2, \qquad . \qquad . \qquad (3)$$

$$\text{and} \quad \sigma^2_{\tau,s} = \sigma_f^2(\tau_1) - \sigma_f^2(\tau_3) \quad \text{for} \quad \tau = \tau_1, \quad s = \tau_3. \qquad . \qquad . \qquad (4)$$

The actual agreement between the above quantities has been determined graphically from the characteristics shown in Fig. 2. For this purpose the transmission curves representing the combined effects of ' sampling ' and ' averaging ' times (according to Eq. 1),

and those representing the differences in ' high-pass ' transmission of corresponding pairs of filters, have been derived for

$$\tau_1/\tau_2 = 6 \quad \text{and} \quad \tau_1/\tau_3 = 36$$

The variances of the transmitted fluctuations are given by the areas under these curves, after weighting according to the shape of the energy spectrum of the input fluctuations. For a spectrum of the form $F(n) \propto n^p$ and with the transmission plotted against n on a logarithmic basis, the appropriate weighting factor is n^{1+p}. The analysis has been carried out for p in the range 0 to -2, which should cover most cases of interest in the atmosphere, and the results are summarized in Table 1.

TABLE 1. RATIOS OF ' MATHEMATICAL ' AND ' ELECTRICAL ' FILTER OUTPUTS (SEE EQS. 1, 3, 4).

p	$\sigma_{\tau_1,\tau_2}/\sqrt{\sigma_f^2(\tau_1) - \sigma_f^2(\tau_2)}$	$\sigma_{\tau_1,\tau_3}/\sqrt{\sigma_f^2(\tau_1) - \sigma_f^2(\tau_3)}$
− 2·0	1·10	1·09
− 1·8	1·07	1·06
− 1·6	1·04	1·04
− 1·4	1·03	1·03
− 1·2	1·03	1·02
− 1·0	1·00	1·00
− 0·8	0·99	0·98
− 0·6	0·97	0·96
− 0·4	0·94	0·94
− 0·2	0·91	0·91
0	0·87	0·87

The deterioration in the agreement as p departs from -1 is a consequence of the poor percentage agreement at the edges of the band-pass transmission curves. As the transmission is low at these frequencies this difference is unimportant when the weighting factor appropriate to the input energy spectrum varies slowly with n, but it becomes increasingly important as the weighting factor varies more rapidly with frequency. In many cases in the atmosphere p will be near to -1 and the values of $\sqrt{\sigma_f^2(\tau_1) - \sigma_f^2(\tau_2)}$ will obviously be an adequate approximation to σ_{τ_1,τ_2}, etc., but when greater precision is desired, the above figures may be useful as correction factors. The necessary estimate of p is already available from the filtered data, since for $\tau_1/\tau_2 = \tau_2/\tau_3 = 6$

$$\frac{\sigma_f^2(\tau_1) - \sigma_f^2(\tau_2)}{\sigma_f^2(\tau_2) - \sigma_f^2(\tau_3)} = 6^{p+1} \qquad . \quad . \quad . \quad (5)$$

in the case of the assumed spectrum $F(n) \propto n^p$. However, the correction will be unrealistic if the energy spectrum is peaked in the frequency range involved, and this condition will not be evident from the above data alone. At least one other value of $\sigma_f(\tau)$, in effect defining a third band in the spectrum, would be required to verify that the power-law form is an acceptable approximation.

3. DETERMINATION OF THE STANDARD DEVIATION OF THE FILTER OUTPUT

The use of a filter as described above reduces the amplitudes of the original fluctuations to those appropriate to a given ' sampling ' time, and the next requirement is to determine the standard deviation of the modified fluctuations in some convenient way. For direct evaluation of the variance the output should be squared but in the present system the simpler process of linear rectification has been adopted. Averaging then provides a modulus mean which can be converted to a standard deviation by application of a factor appropriate to the form of the fluctuations. The usual assumption which is envisaged here is that the fluctuations will have a near-Gaussian distribution of amplitudes, for which the ' form-factor ' will be a good approximation to $\sqrt{\pi/2}$.

Some smoothing of the rectified output may be introduced electrically by a ' meaning ' circuit, i.e., a ' low-pass ' filter, and the slowly varying final output may then be recorded with a relatively slow chart speed. The averaging thus imposed should be kept to a minimum consistent with the production of a readable record, so that the time lag also introduced electrically will be as small as possible. Further averaging may then be provided numerically by reading the record over some period, and a good statistical average of the standard deviation will thus be obtained. The upper limit of the effective averaging time is a matter of choice, according to the sort of variation in intensity of turbulence which it is desired to study. There will however be some lower limit below which error will probably be introduced by departure of the form factor from the assumed $\sqrt{\pi/2}$. In the tests and proposed applications now to be discussed, averages over about one hour are deliberately sought, and in these cases it will be seen that adequate accuracy may be obtained.

4. Practical details

The frequency range required to be covered by the system extends from an upper limit governed by the response characteristics of the sensing head down to a frequency approaching 1 cycle/hr. With the use of a suitable type of sensing head the upper limit could extend into the audio range, but for the vane-type instrument which is used at present the upper limit is a few cycles per second. Capacitor-resistance filter circuits are used because for these low frequencies inductors would be of prohibitive size and expense.

Despite the exceedingly low frequencies involved it was found possible to use standard types of capacitor and valve throughout, by taking special precautions to minimise leakage currents. With the chosen operating voltages (Fig. 3) grid current is sufficiently low to have negligible effect on linearity, and special electrometer valves are unnecessary.

(a) *The filter circuit*

The two-stage circuit, with $C_1 = C_2$ and $R_1 = R_2$, is shown in the first section of Fig. 3. Valve V_1 acts as a buffer preventing mutual interaction between stages, and also as an amplifier to provide the necessary degree of sensitivity for recording. Amplification is preferably introduced at this stage rather than later, so that any very long-period zero

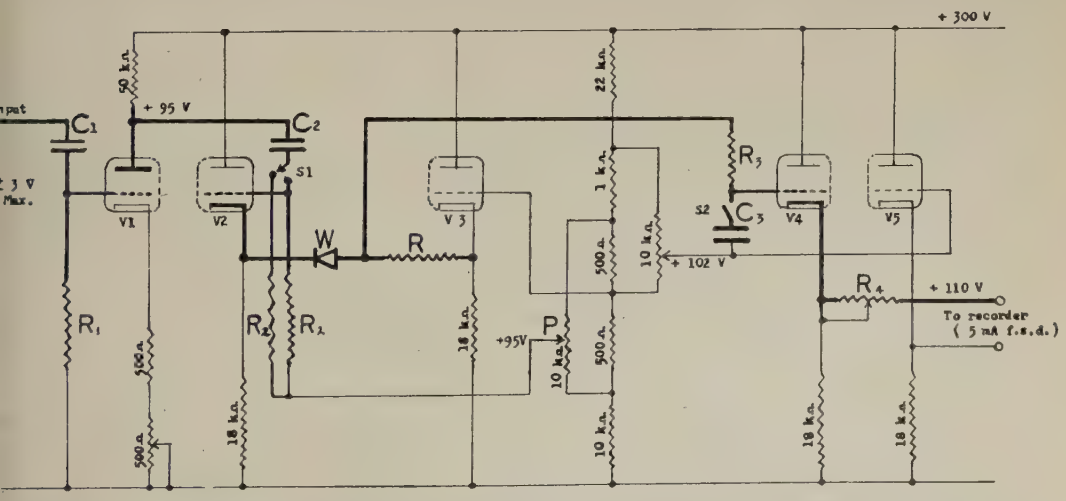

Figure 3. Circuit diagram of one unit providing filtering, rectifying and meaning. All valves are type CV 1988 (6SN7). Switches S_1 and S_2 are positioned for adjustment to the diode working point by means of potentiometer P and for checking the zero.

drift in the amplifying valve (the main source of drift) is ' blocked ' by the second stage of the filter circuit. To minimise leakage currents through the capacitors, the circuit is designed to maintain near-equal static potentials between capacitor plates and between plates and screening case. Thus the *mean* input voltage should be as near as practicable to earth, though values up to at least 10 v can be tolerated even with the largest CR value (101 sec) used. Leakage in C_2 is minimised by equalizing the static potential difference between the anode of V_1 and the grid of V_2, while the screening case of C_2 is maintained at the same static potential as its plates. With these precautions, it was found possible to obtain satisfactory operation using ordinary ' block-paper ' type capacitors selected for high-insulating resistance.

(*b*) *The rectifier*

The output of the filter circuit is passed through the cathode-follower V_2 to the rectifying circuit consisting of a silicon junction diode W and resistor R. This circuit is connected between the cathode of V_2 and the ' steady ' cathode of V_3, and half of the filtered signal is reproduced across R. Rectification takes place at a relatively high-amplitude level, and this, together with the sharp cut-off and high forward-reverse resistance ratio of the silicon diode, maintains good linearity throughout the working range. Correct setting of the working point of the rectifier is made with a ' pre-set ' potentiometer P. The choice of half-wave rectification was made for the sake of simplicity but full-wave rectification could equally well be used by adding a second rectifying circuit. This would permit ' meaning ' of the output over half the period required with half-wave rectification, which latter is the period of the lowest frequency for which the filter has significant response. It would also provide double the sensitivity but otherwise the quality of the output would be unchanged.

(*c*) *The meaning circuit*

A running mean value of the negative half of the filtered signal is provided automatically by the meaning circuit, $R_3\,C_3$, in which the insulation resistance of C_3 is very much greater than R_3 and also $R_3 \gg R$. The circuit is in effect a single-stage low-pass filter and similar precautions to those used in the high-pass filter circuits are used to minimise leakage currents in C_3. The fluctuating voltage across R is reproduced across C_3 as a slowly varying mean and passed on to the cathode-follower output valve V_4 and hence through an adjustable attenuator R_4 to the recorder.

(*d*) *Calibration*

As noted previously the equivalent ' sampling time,' τ, is given by $0{\cdot}44/n'$, where n' is the frequency for which the filter transmits 50 per cent of the power of the input signal. Since for a 2-stage filter $n' = 0{\cdot}247/CR$, the value of CR appropriate to the required value of τ is given by $\tau/1{\cdot}78$. The nominal values of C and R selected for ' sampling times ' $\tau_1 = 180$ sec, $\tau_2 = 30$ sec and $\tau_3 = 5$ sec are as follows :

TABLE 2. Characteristics of the high-pass filters

τ (sec)	n' (c/sec)	$C_1 R_1$ (sec)	C_1 (μF)	R_1 ($M\Omega$)
180	0·0025	101	10	10
30	0·0147	16·9	4	4
5	0·088	2·8	1	3

A sine-wave oscillation of frequency $\simeq 0{\cdot}44/\tau$ (near 50 per cent power-transmission frequency) was then fed into the filter circuit and an adjustment of the resistance in one of the stages made so that the response matched the theoretical response at this frequency. Transmissions were then checked at other selected frequencies and are shown compared with the theoretical values in Fig. 2.

To set the sensitivity of the complete circuit, a sine-wave signal voltage of sufficiently high frequency to ensure near 100 per cent transmission was fed into all three filter circuits. The frequency used was either 50 c/sec from an a.c. mains source or 1·1 c/sec from a mechanical generator. If the modulus mean of the input voltage is v then the output signal passed to the recorder will be equivalent to a modulus mean velocity of v/V, where V is the output sensitivity of the sensing head, e.g. voltage per unit change in wind velocity. To record as a standard deviation rather than a modulus mean, the output is taken as being equal to Fv/V where F is the ' form factor ' of the wave form emanating from the filters. For convenience of reading the record, the calibrating input signal is then matched to the scale of the recording chart by adjustment of the sensitivity of the ' sensing head ' or of a variable resistance R_4 in series with the recorder, or both.

The sine-wave generator used to produce the calibrating signal was of electro-mechanical construction. A mains synchronous electric motor was connected by reduction gearing to a ' Scotch cam ' mechanism. This produced true simple harmonic motion, which was transferred to the moving contact of a linear high resolution potentiometer. Provision was made for changing the gear ratio to provide a frequency range of 1·1 to 0·0004 c/sec.

5. Some tests of the system

Some direct tests of the system have been made using a responsive wind vane coupled to a low-friction potentiometer so as to provide a voltage output proportional to the deviation of the wind direction from some arbitrarily fixed bearing. This voltage output was used to give a conventional time-lapse record on a chart moving at 1 in./min in addition to the three records of standard deviation, corresponding to sampling times of 180, 30 and 5 sec respectively, on a chart moving at 0·1 in./min. Values of $\sigma_{\tau,s}$ for a sampling time of 180 sec and an averaging time of 5 sec were computed from the time-lapse trace, and also from the corresponding records of standard deviation by using Eq. (4), for periods of about one hour.

Comparisons have been made using three sets of observations obtained with the instrument mounted at a height of 10 m with a good exposure to the wind over open downland. A summary of the results is given in Table 3. Set 1, on 29 July 1958, was carried out with a surface windspeed near 8 m/sec, so that despite the lapse of temperature prevailing in the first few metres above ground the stability conditions were effectively neutral. On 9 Oct. 1958 the wind was much lighter, decreasing from 4 to 1 m/sec during Set 2 and being maintained steadily at about 4 m/sec for Set 3, and the conditions were effectively slightly unstable and slightly stable respectively.

TABLE 3. Test values of $\sigma_{\tau,s}$ for wind-direction variation (sampling time τ 180 sec and averaging time s 5 sec). (a) computed from the time-lapse trace; (b) from the electrical-filter system, using Eq. (4) with τ_1 and τ_3 180 and 5 sec respectively.

Set	Date	Period (GMT)	$\sigma_f(\tau_1)$	$\sigma_f(\tau_2)$	$\sigma_f(\tau_3)$	$\sigma_{\tau,s}$ (a)	$\sigma_{\tau,s}$ (b)
1	29 July 1958	1430-1530 (approx.)	5·71	4·30	2·67	5·2	5·0
		1545-1645	6·25	4·35	3·17	5·4	5·4
2	9 Oct. 1958	1428-1528	6·81	4·63	3·05	5·6	6·1
		1443-1543	6·29	4·40	2·83	5·6	5·6
		1458-1558	6·14	4·38	2·83	5·4	5·4
3	9 Oct. 1958	1615-1700	4·27	4·14	3·07	3·1	3·0

Without making any corrections for the difference between the ' electrical ' and ' mathematical ' filter characteristics it will be seen that the agreement is good except in the first period of Set 2. As the agreement would in fact become worse if the latter corrections were applied, the reasons for this discrepancy were investigated in some detail. At least three sources of error seemed to be possible, firstly in the assumption of a ' form factor ' appropriate to a Gaussian distribution, secondly in the relatively different statistical sampling which is involved in deriving $\sigma_{\tau,s}$ by the two methods (in (*a*) consecutive non-overlapping 180-sec periods are involved, whereas in (b) a continuous overlapping of 180-sec periods is implied), and thirdly in the lag effects introduced in the electrical recording.

From a detailed analysis of the observations of Set 2 it ultimately appeared that the main source of discrepancy was the third possibility listed above. The record of $\sigma_f(\tau_1)$ contained prominent maxima at intervals of about 18 min average, and it was found that the variation of $\sigma_{\tau,s}$ as derived from the time-lapse record contained similar features about 2 min earlier. This is clearly a case of lag due to the meaning circuit, and indeed the magnitude of the lag agrees well with the theoretical value of 2·1 min appropriate to a period of 18 min and the *CR* value of 150 sec then involved. It may seem surprising that such a small lag should be significant when comparing values averaged over an hour but the reason evidently lies in the substantial variations in $\sigma_{\tau,s}$ from maximum values near 10° to minimum values near 3°. The net effect on the hourly averages is shown in Fig. 4 as is also the agreement obtained when the lag of 2 min is introduced. In particular the original discrepancy of 0·5° is reduced to 0·2°.

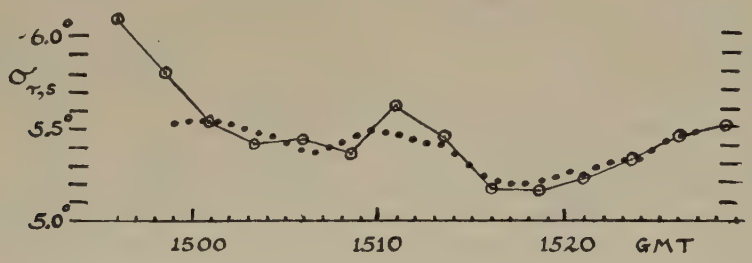

Figure 4. Detailed variation of hourly averages of $\sigma_{\tau,s}$ for Set 2 of Table 3.

• • • • from time-lapse record.

⊙——⊙ from electrical filter system, plotted 2 min earlier to allow for lag effect of meaning circuit.

The time scale refers to the mid-point of the hour over which the average is taken.

In forming the hourly averages for Fig. 4 overlapping 3-min samples of the conventional time-lapse trace were used, the beginning of the samples being at $\frac{3}{4}$ min intervals. It is interesting to note that values derived in this way differed by 0·1 or 0·2 from the corresponding three values originally derived from non-overlapping samples, indicating that even over a long period the extra sampling provided by an overlapping process may be desirable. Such a process is of course provided automatically in the electrical system.

The ' form factors ' which were also computed in the detailed investigation of Set 2 are noteworthy. They have been obtained from individual values of the standard deviation and modulus mean, and also from means formed from overlapping values over total periods of 15, 30 and 60 min. A summary of the results is given in Table 4. Evidently the form factor may depart substantially from the assumed value of 1·25 when individual cases are considered, but when mean values are formed the discrepancy is greatly reduced and falls to a negligible amount when the mean is taken over about 1 hr.

TABLE 4. FORM FACTORS (i.e., standard deviation/modulus mean) FOR SAMPLING TIME τ (180 sec) AND AVERAGING TIME s (5 sec)

Data used	No. of values of form factor	Range of form factor
Individual values	117	1·06-1·54
15-min means	99	1·18-1·28
30-min means	78	1·21-1·26
60-min means	38	1·23-1·24

For Sets 1 and 2 the values of p derived from Eq. (5) fall in the range $-1{\cdot}1$ to $-1{\cdot}4$, and the maximum correction factor which should then be applied to $\sigma_{\tau,s}$ as obtained electrically is thus about 1·03 (see Table 1). In Set 2 at least it is now evident that part of this correction is already implied by the assumption of 1·25 for the form factor, instead of 1·23 or 1·24 as actually observed, and the overall correction required is evidently negligible. A very different situation arises for Set 3, where the value of p appears to be near zero. This implies a correction factor of 0·87, and as the form factor determined for this case is actually 1·24, the overall correction to be applied would considerably worsen the agreement between the two values of $\sigma_{\tau,s}$. It may be seen, however, that this is one of the cases where the determination of p from the three values of $\sigma_f(\tau)$ is quite misleading. The apparent value of p ($\simeq 0$) so obtained is merely an effective value applying to a frequency band between about 0·088 and 0·0025 c/sec, (i.e., a ratio of 36 : 1 in frequency). Since the vane response characteristics (described later, see Fig. 5) are equivalent to the transmission of a ' low-pass ' electrical filter with a 50 per cent power transmission at about 3 c/sec (i.e., a frequency approaching 36 times 0·088), it follows that

$$\frac{\sigma_f^2(\tau_1) - \sigma_f^2(\tau_3)}{\sigma_f^2(\tau_3)} \simeq 36^{p+1} \quad . \quad . \quad . \quad . \quad (6)$$

where p will now be an effective value over the frequency range 3 to 0·0025 c/sec. For Set 3 the R.H.S. of Eq. (6) is close to unity so that p is close to -1. These results mean that the spectrum of $n\,F(n)$ has a sharp peak somewhere between 0·088 and 0·147 c/sec and this is a region in which the percentage agreement of the electrical and mathematical filter characteristics is at its best.

In practice it would appear that when the value of p implied by Eq. (5) is near -1, the correction for the filter characteristics may be neglected, whether the true spectrum of $n\,F(n)$ is flat or sharply peaked. Likewise, if values different from -1 are obtained but appeal to Eq. (6) as above indicates that the spectrum is in fact sharply peaked the correction may again be neglected. On the other hand if appeal to Eq. (6) substantially confirms the original estimates of p it would clearly be desirable to apply the corrections given in Table 1.

6. CURRENT APPLICATIONS

Although further work is envisaged on the design and performance of this system, it is clear that the present form already provides an opportunity of acquiring certain statistics in a quantity which has not hitherto been readily obtainable. Two applications which are at present being actively developed concern wind direction fluctuations near the ground and wind inclination fluctuations at various heights up to a few thousand feet above ground.

As already mentioned, statistics of the standard deviation of the wind-direction fluctuations are relevant to the lateral spread of airborne material. A ' climatological ' study is now proposed in which these statistics will be examined in relation to the broad meteorological conditions. The instrument to be used is the responsive wind vane already referred to in the previous section and some further details may now be of interest.

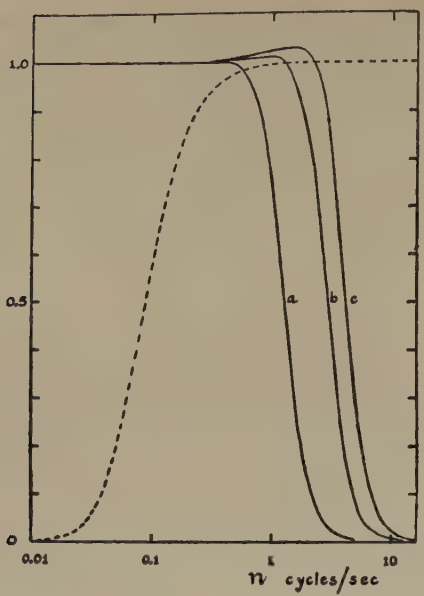

Figure 5. Computed (response)^2 of wind vane to sinusoidal oscillations at wind speeds of (a) 2 m/sec (b) 5 m/sec, (c) 8 m/sec. Broken curve is the power transmission of a two-stage high-pass filter with $CR = 2{\cdot}8$ sec.

With the object of keeping the inertia of the vane assembly as low as possible the vane itself was made of balsa wood and waterproofed tissue paper, and the usual counter-balancing head was eliminated. An examination of the response characteristics of the instrument was made in the wind tunnel, by releasing the vane from a deflected position in the airstream, and recording the output on a high-speed recorder. From these records and classical solutions for forced oscillations the approximate response of the vane to oscillations of wind direction, i.e. the fraction of the wind direction variation which is indicated by the vane, has been calculated for various frequencies. The squares of the response are shown in Fig. 5, with the power transmission curve of the filter of CR-value 2·8 sec. Since the response of the wind vane does not depart appreciably from 100 per cent until the transmission of the filter has reached nearly 100 per cent this means that in the use of Eq. (4) (with $\tau_3 = 5$ sec) there will be no important error due to inadequate response of the vane unless relatively important amounts of turbulent energy exist at frequencies of 1 c/sec. From the available knowledge on the spectrum of atmospheric turbulence the latter condition is only likely to arise near the ground in stable conditions, when, in any case, the absolute level of turbulence is low.

Movement of the potentiometer contact driven by the vane is limited to an arc of 300° by mechanical stops. With the object of avoiding the inconvenience of manually resetting the orientation of the instrument at frequent intervals the vane and potentiometer spindles are connected frictionally by a light clutch. This clutch is released by light pressure of the contact arm against the potentiometer stop and re-setting thus occurs automatically. Some error will be introduced on these occasions, since a part of the wind variation will be eliminated from the output of this instrument. Thus if the wind direction variation contains a steady component of θ per hour the error in the variance for $\tau = 180$ sec will be $\theta^2/4800$, which will usually be negligible. On the other hand, if the mean wind direction changes suddenly by an amount θ the error in the variance, even when spread out over 1 hr, may be as much as $\theta^2/80$. However, it will be evident from a routine wind-direction trace when the latter value is likely to be important. The actual existence of error can then be positively checked by calculating the position of the contact from a knowledge of a previous setting of the instrument.

The instrument will normally be mounted at a height of 16 m, with a good exposure to the wind over open downland. It is proposed that recording shall be carried out with a chart speed of $\frac{1}{2}$ in./hr, so that a 24-hr record will be compressed into a chart of convenient size. Some trial recordings (actually at a height of 10 m) have already been made and an example is shown in Fig. 6. For this case the *CR*-values of the meaning circuits were 500, 230 and 100 sec for sampling times of 180, 30 and 5 sec respectively. This means that the lag of the 180-sec record for all variations with a period greater than 2 hr will be about 8 min (i.e., equal to the *CR*-value), while with a period as short as 20 min the lag is nearly 4 min. In expressing the general diurnal variation by taking averages over 1 hr it will evidently be adequate to allow a general lag equal to the *CR*-value in each case. It should of course be remembered that averaging over some period is already imposed by the 'meaning' circuit and for a single-stage circuit as used this period will be approximately 3 *CR*, i.e., about 25 min in the present case for $\tau = 180$ secs. The first half-hour of this particular record for $\tau = 180$ sec should be disregarded as it may be in error owing to the initial build-up of the potential across the condensers of the filter circuit after switching on. Errors of this sort may always be present when the input signal to the filter circuit is interrupted, but they can be eliminated from daily records by allowing continuous operation of the filter while carrying out zero checks. In practice this is arranged by positioning switches S_1 and S_2 as shown in Fig. 3.

Figure 6. Specimen daily record of standard deviation of wind direction for sampling times (τ) of 5, 30 and 180 sec.

The record is of particular interest in containing a diurnal variation which is the more pronounced the longer the sampling time τ. This is of course due to the introduction of fluctuations of relatively low frequency, a feature which is in no way surprising for the middle of the day when convective processes were active. However the large values occurring between 0130 and 0500 GMT are rather remarkable in that they are associated with very light wind (the Dines anemograph record is evidently useless over this period) and an apparently high degree of stability. These bursts of turbulence may be examples of the breakdown in the stable layer under the action of wind shear, similar to that discussed by Durst (1933), but a full analysis of the situation is not possible in the absence of data on the wind profile and the vertical component of turbulence.

Measurements of the fluctuations of wind inclination are being made occasionally at Cardington, Bedfordshire, using equipment described elsewhere (Jones and Butler 1958). The 'sensing head' for wind inclination is a light vane operating a potentiometer, and the output may be recorded with the equipment described in this paper, instead of or in addition to the usual time-lapse record. Once again the present system offers the prospect of acquiring comprehensive statistics without prohibitive numerical work.

Finally, although the system was developed with the specific requirements of certain diffusion studies primarily in mind, it is perhaps worth noting that the data obtainable may have much more general application. The quantities directly recorded could be used to form estimates of the turbulent energy in ' spectral windows ' which may be regarded as approximately equivalent to spectral bands as follows :

' Energy '	*Equivalent frequency band (c/sec)*
$\sigma_f^2(\tau_1) - \sigma_f^2(\tau_2)$	0·0025 — 0·0147
$\sigma_f^2(\tau_2) - \sigma_f^2(\tau_3)$	0·0147 — 0·088
$\sigma_f^2(\tau_3)$	0·088 — n_0

The quantity n_0 is the frequency at which the ' power ' response of the vane is 50 per cent. These limits apply only to an energy spectrum in which $nF(n)$ is constant, i.e., the exponent p in the power law form $F(n) \propto n^p$ is -1. For other values of p the effective positions and widths of the bands will be different by amounts which may be assessed by a graphical analysis similar to that carried out in deriving Table 1.

Acknowledgment

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The small-ion concentration and space charge near the ground

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SUMMARY

A series of detailed measurements was made of the concentration of small ions near the ground. It was found that for values of the atmospheric potential gradient exceeding some $\pm$ 500 v m^{-1} the electrode effect in the small ions was readily observable, and that when rain fell in a large electric field, there took place a large production of ions of sign opposite to that of the field. The latter effect was examined in some laboratory experiments which showed that the release of charge in the form of ions was associated with splashing. The mechanism by which the ions were produced was found and a determination made of the dependence of the charge released by individual drops on the field, drop mass and drop speed at impact.

To determine the importance of the charge released by splashing at the ground, another series of observations was made including the measurement of space charge. It was found that in fine weather the field was sometimes controlled by clouds of charge near the ground. In disturbed weather natural point discharge gave rise to considerable values of the space charge, and in comparison with these, the charges produced by the splashing of rain only became important during heavy rain.

1. The concentration of small ions near the ground

(*a*) *Introduction*

It has been found that the negative fields* which are observed at the ground during steady rain are sometimes associated with negative charge near the ground. In search of an explanation of the origin of this charge, Smith (1955) recalled that the breaking-up of water releases negative charge to the air, and he was able to deduce a relation between the rate of rainfall and the potential gradient. A search for any such effect was started by making measurements of the small-ion concentration near the ground during various weather conditions, using a continuously recording instrument of short time constant. For this purpose an Ebert counter of conventional design was arranged to collect all ions of one sign with mobilities exceeding 0·25 cm $sec^{-1}/v\ cm^{-1}$, and by using a vibrating-reed electrometer to measure the current an effective time resolution of a few seconds was achieved. Elaborate precautions were taken to safeguard the reliability of the measurements in all weather conditions, and careful electrical screening ensured the non-interference of external fields. No attempt was made to obtain an accurate absolute calibration of the counter because interest lay primarily in the variation of ion concentration with changes in conditions.

During periods of observation, continuous records were also made of the electric field and occasionally of the wind speed and the discharge from a point at a height of about 10 m. Rainfall, humidity and temperature data were provided by the routine laboratory records. Nearby buildings and trees probably provided some electrical screening of the field mill, and their presence may account for the somewhat reduced fields which were observed. For time and zero checks on the records from the ion counter and field mill, both inputs were earthed for the half minute preceding each half hour.

(*b*) *Results in undisturbed conditions*

The number of ions counted during fine weather varied greatly, but was normally between 150 and 500 cm^{-3} with a mean of about 250 cm^{-3}. It was sometimes found that a considerable rise in the concentration of ions of both signs followed rain, presumably due

* I use the terms 'field' and 'potential gradient' synonymously, taking both as positive when a positive charge would experience a downward force.

to the washing out of nuclei or the arrival of cleaner air. The increase in concentration sometimes lasted many hours. There were also occasional increases associated with particular wind directions and these were taken to correspond to local sources of ions. The distance at which such a source can be detected is set primarily by the wind speed and the mean life of the ions. As the latter is only about half a minute, the sources would be expected to lie within a few hundred metres. It seems likely that a nearby transformer sub-station was responsible for at least some of the ions.

(c) *The electrode effect*

'Electrode effect' is used here to denote the dependence of the ion concentration near the ground on the electric field. When the field is large, ions of sign opposite to that of the field will be removed quickly from the air near the ground. Provided that the turbulent mixing is not too great, a consequent reduction in the concentration of ions of that sign will then be observed there, while the number of ions of the same sign as the field will remain unaffected.

It was found that fields greater than 500 v m^{-1} normally produced a clear electrode effect in the small ions at a height of 110 cm (the level of the air intake for the counter). During the periods of enhanced ion concentration after rain, the field was able to move the ions further from the ground during their lifetime and much smaller fields sufficed, the concentration of the small ions showing a strong dependence on field changes of a few hundred volts per metre.

Fig. 1 shows the electrode effect as it took place during a period of enhanced ion concentration after rain. Apart from a little light rain between 2130 and 2200 hr, there was none during the period shown. The short pulses which are associated with the half-hour marks, here and in some of the illustrations, are instrumental.

It should be pointed out that the correspondence between the field and ion records in the electrode effect cannot result from preferential sampling of the ions by convergence of the electric field at the apparatus. (1) The speed with which the ions move under the action of all but the largest fields will normally be many times smaller than the speed with which they are carried by the wind, so that the field will play no significant part in carrying them to the counter, and (2) it should be noted how the measured ion concentrations are independent of field changes while the field is of the same sign as the ions being counted. If preferential sampling were taking place, this would not be so. For instance, a positive field would drive positive ions towards the apparatus.

All the experimental results were in agreement with the following theory.

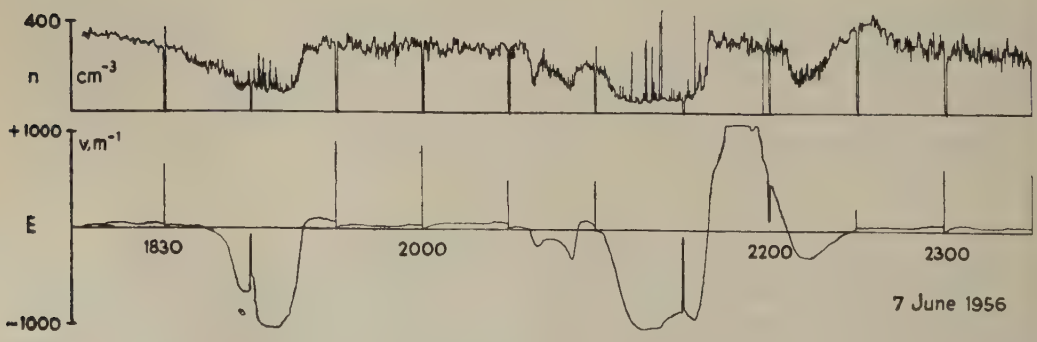

Figure 1. The electrode effect. Simultaneous records of the concentration of positive small ions and the potential gradient.

(d) *Theory of the electrode effect*

The local rate of change of ion concentration is given by

$$\frac{\partial n}{\partial t} = D\,\nabla^2 n - wE\,\nabla n + q - \frac{n}{\tau} \quad . \quad . \quad . \quad (1)$$

where

n cm^{-3}	=	ion concentration
D cm^2 sec^{-1}	=	eddy diffusivity for the ions
w cm sec^{-1}/v m^{-1}	=	mobility of the ions
E v m^{-1}	=	electric field
q cm^{-3} sec^{-1}	=	rate of production of the ions
τ sec	=	half life of the ions

To indicate the behaviour of the ions under natural fields, it will be sufficient to obtain solutions for n when a vertical field is applied suddenly to any initially uniform distribution of ions, that is, subject to the conditions

$$t < 0 \quad \text{then} \quad E = 0 \quad \text{and} \quad \begin{cases} n = n_0 & \text{for} \quad h > 0 \\ n = 0 & \text{for} \quad h < 0 \end{cases}$$

$$t > 0 \qquad E = E$$

where h is the height above the ground.

We may proceed to an approximate solution by considering separately what happens to the original ions, and the way in which repopulation is brought about by the formation of new ions.

(*i*) Under the action of the field, the original distribution, a step function at $h = 0$, will move upward at a speed wE cm sec^{-1}. Then, ignoring the change of population, the behaviour of the original ions will be equivalent to the diffusion of a step function of concentration, but with the whole moving upward at wE cm sec^{-1}.

The appropriate equation is

$$\frac{\partial n}{\partial t} = D\,\nabla^2 n - wE\,\nabla n$$

giving the solution

$$n = f(Eht) = \frac{n_0}{2}\left[1 + \phi\left(\frac{h - wEt}{2\sqrt{Dt}}\right)\right] \quad . \quad . \quad . \quad (2)$$

where ϕ is the error integral

$$\phi(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-\xi^2)\, d\xi$$

In his study of turbulent diffusion over short grass, Rider (1954) obtained diffusivities of around 10^3 cm^2 sec^{-1} at 75 cm above the surface, with wind speeds of about 5 m sec^{-1}. Values vary with wind speed and height, but in the present calculations we will adopt this value as being typical.

(*ii*) The concentration due to creation and loss of new ions alone is given by the equation

$$\frac{\partial n}{\partial t} = q - \frac{n}{\tau}$$

If we consider the time for which a group of ions has existed, we may make the substitutions

$$t = t \quad \text{for} \quad h > wEt$$

$$\text{and} \quad t = \frac{h}{wE} \quad \text{for} \quad h < wEt$$

(A group at height $h < wEt$ will have been at the surface h/wE sec before, and therefore will only have existed for h/wE sec). We then arrive at the solutions

$$\begin{aligned} n = F(t) \quad &= n_0 [1 - \exp(-t/\tau)] \quad \text{for} \quad h > wEt \\ n = F(Eht) &= n_0 [1 - \exp(-h/wEt)] \quad \text{for} \quad h < wEt \end{aligned} \qquad (3)$$

To obtain good solutions of Eq. 1 we can combine the distributions indicated by Eqs. 2 and 3, remembering that the contribution of Eq. 2 will itself be reduced with time constant τ by loss of original ions. For $t \gg \tau$ the contribution of Eq. 2 will vanish and the distribution will be determined by Eq. 3 alone. We therefore have a close approximation to the solution of Eq. 1 by putting

$$n = F + f \exp(-t/\tau)$$

In Fig. 2 solutions obtained in this way are shown for various values of the field taking $t = 15$, a time short compared with the life of the ions. In Fig. 3, with $t = 120$, the steady states have been reached. It must be remembered, however, that in the construction of these last curves diffusion has been neglected. This will be important where large concentration gradients occur, so that the curve for a field of 500 v m^{-1} is probably a slight overestimate of the electrode effect.

The more important predictions of the theory may be summarized as follows :

(*i*) At a height of 1 m, fields of 500 v m^{-1} give a reduction of about 30 per cent in the concentration of small ions of opposite sign. The electrode effect should therefore be readily observable for fields greater than this, while it will become obscured by the normal fluctuations in concentration for smaller fields.

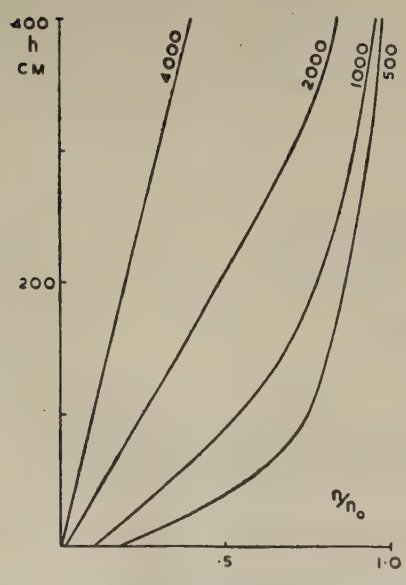

Figure 2. The electrode effect as a function of height 15 sec after the application of various fields.

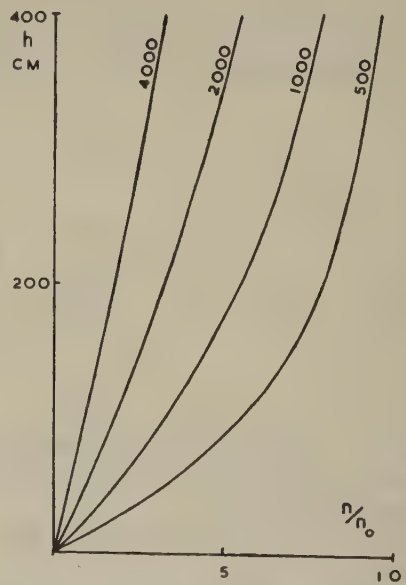

Figure 3. The electrode effect as a function of height 120 sec after the application of various fields.

(*ii*) Near-equilibrium values of the ion concentrations are reached within 30 sec of a field change.

(*iii*) If the mean life of the small ions is increased in any way, the electrode effect will be more pronounced.

(*iv*) In fine-weather potential gradients, the concentration of the negative small ions should fall off significantly below about 1 m. (This is in agreement with Hogg's (1939) results).

(*e*) *Ion production*

During rain, in small fields, it was found that the concentrations of ions of both signs were often disturbed. In larger fields there took place a very large production of ions of sign opposite to that of the field for fields of either sign, in all but the lightest rain. If ions of both signs were produced at such times, and the laboratory experiments (see § 2) suggest that they were not, then those ions of the same sign as the field were immediately lost to earth. At no time was there any indication of a systematic tendency to release ions of either one sign. There is therefore no evidence of the release of charge in ions of high mobility by the Lenard effect (i.e. by a process which is independent of the field). The field-controlled production of ions, however, is of considerable importance, as the total charges can be large and may modify severely the fields observed at the ground. (This is demonstrated directly in § 3.)

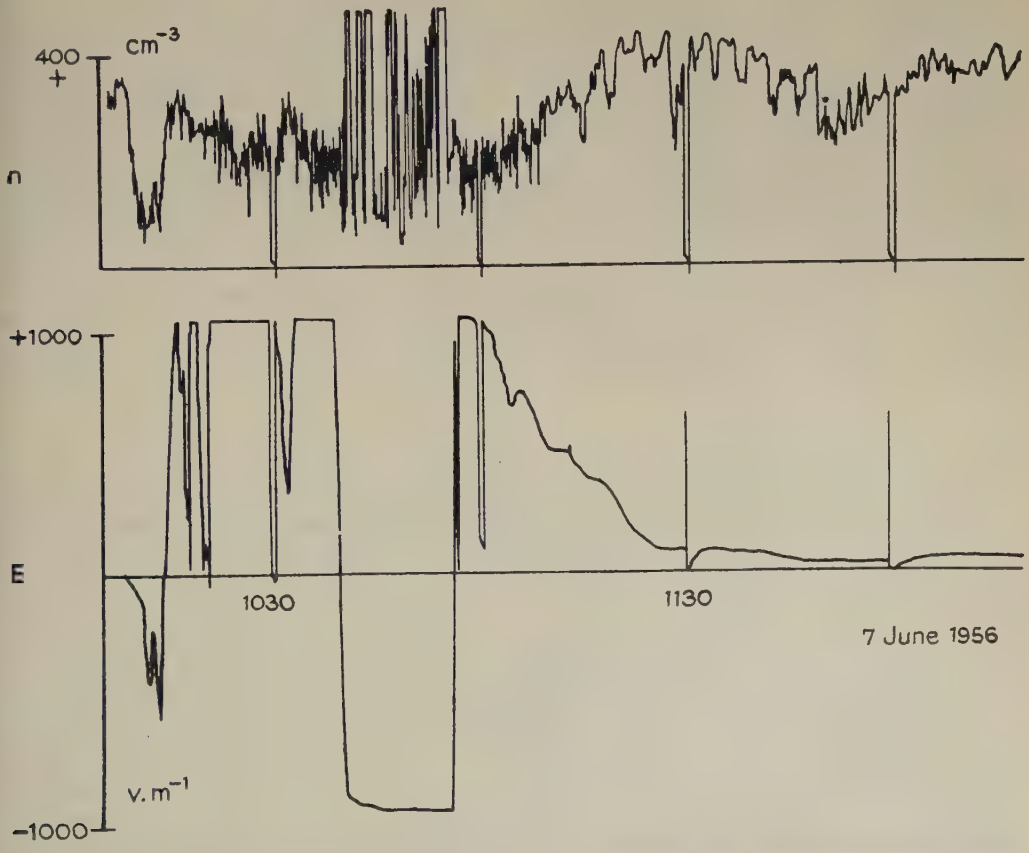

Figure 4. Ion production in rain. Simultaneous records of positive small-ion concentration and the potential gradient.

Fig. 4 shows an occasion when positive ions were produced in a negative field. Rain was falling at about 2 mm hr^{-1} until 1100 hr. While the field remained positive the positive ion concentration was disturbed but there was little change in the mean level. During the period of strong negative field, large numbers of positive small ions were produced. The rise above normal of the ion concentration after the rain should be noted.

The laboratory experiments of § 2 indicate that these ' small ions ', which are produced by splashing, are extremely small water droplets carrying an electric charge. Whether, like normal small ions, they consist of a dozen or so water molecules with one electronic charge, or are more highly charged, larger droplets, it is impossible to say from the present measurements; but as they appear to behave exactly like small ions in the processes involved here, the term is used without further qualification.

2. Laboratory experiments

(*a*) *The nature of the experiments*

Previous workers have observed electrical effects associated with the breaking of drops, but Gill and Alfrey (1952) suggest that all their results can be explained in terms of induced charges resulting from contact potentials between the water and parts of the apparatus, and that the observed ' ions ' were highly-charged fragments which need not necessarily have acquired their charge at the time when the drops were broken. If their argument is true, when a drop splashes on a surface, it should be possible to control the charge released in the form of these ' ions ' by the application of an external field. This would give rise to a field-controlled release of charge similar to that found in the experiments of § 1.

To avoid any spurious effects in the present experiments every precaution was taken to ensure that the processes in the experiments were exactly analogous to those in the atmosphere. In particular, all drop fragments which would normally fall to the earth must be collected, and the currents measured must correspond to those ions which would move upwards from the surface under the action of the atmospheric field. Further, movement of air in the apparatus must be avoided, thus eliminating any electrical effects associated with the contact of splash fragments with other parts of the apparatus in the way envisaged by Gill and Alfrey.

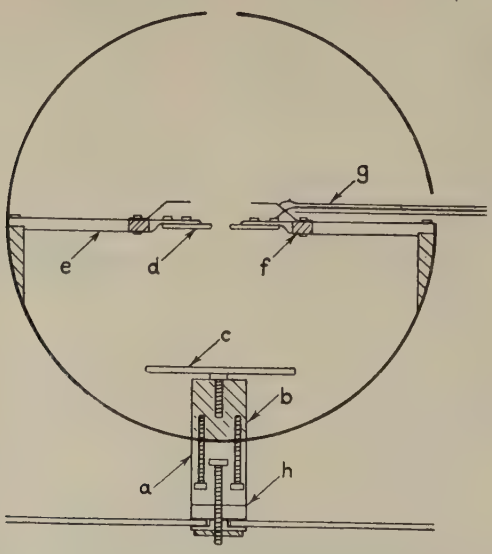

Figure 5. The sphere apparatus.

Preliminary experiments showed that when drops splashed on a smooth metal surface, fragments hardly ever rose within 30° to the vertical, provided that the surface was not covered with more than about 1 mm of water. This suggested the design shown in Fig. 5. Within a large metal box, an aluminium sphere of 31 cm diameter was supported on a single polythene insulator, a. Inside the sphere, a brass block, b, supported a circular target, c, on which the drops splashed. The field at the surface of the target was controlled by varying the voltage on an aluminium disc, d, the field electrode, supported vertically above the target on polystyrene insulators, e, equipped with earthed guard-rings, f. The voltage was applied to the field electrode via E.H.T. cable introduced into the sphere through heavy $\frac{1}{4}$in. brass tubing, g, earthed to the outer box. The drops were allowed to fall from a shielded dropper, through holes in the box, sphere and field electrode, their charge being adjusted by varying the potential on the shield. Throughout the experiments, uncharged drops of tap water were used. The position and size of the field electrode were such that fragments from splashed drops virtually never reached it. Its lower surface was examined occasionally during measurements to confirm this. All sharp corners in the apparatus, in particular the edges of the field electrode and its associated conductors, were coated with paraffin wax to prevent point discharge; and the very bottom of the sphere was waxed to prevent leakage of water to the insulator or its fixing bolts.

The analogy between the processes in the apparatus and the atmosphere is very close. The sphere and the target represent the ground and the field electrode the source of the field at the ground. When a drop splashes, all fragments are returned to ground, and the current flowing into the sphere consists only of those ions which are produced within the sphere and removed by the field, their charge leaving the sphere by the field electrode and its associated circuit. It should be pointed out that only those ions of sign opposite to that of the field will be removed from the sphere, any others being returned to the target or sphere. The analogy may, therefore, depart for very low fields when, in the atmosphere, if any ions of the same sign as the field are produced they may not all be returned to ground owing to the turbulent air motions near the surface. Apart from this, the current flowing into the sphere corresponds directly to the charge released from the ground.

The current from the sphere was fed to the vibrating-reed electrometer through an integrating circuit with a total time constant of about 30 sec. The insulator guard ring, h, and the earthy end of the integrating capacitors were returned to the electrometer negative feedback line so that any insulation failure immediately returned the electrometer reading to zero. To find the average charge released by individual drops, the mean current was divided by the rate of dropping as determined by timing a number of drops. The field at the centre of the target as a function of the voltage on the field electrode was determined empirically.

(*b*) *Results*

It was found that ions of sign opposite to that of the field were produced when drops splashed on the target in fields of either sign. Preliminary experiments showed that the charge released in this way increased with field, drop mass and drop speed. It was also strongly dependent on the nature of the target. If the target was ' soft ' so that little splash occurred, little charge was released, while if the target was ' hard ' so that drops splashed violently, considerable charge was released. It was also found difficult to obtain a target which remained stable in this respect.

A freshly cleaned and wetted brass disc with wicks of surgical gauze hung from its edges to maintain the surface film of water at about 0·5 mm thickness, although soft, was found to be moderately reproduceable. This target was first used for a series of experiments in which different sized drops were released from various heights above the target to find the charge released in a fixed field. Over the range of heights used none of the drops approached its terminal velocity so the height can be taken as proportional to the drop energy at impact. The measurements were repeated several times to obtain a good average against the target variations. Fig. 6 shows the charge released by the drops as a function of the height at which released. For any one drop the relation is linear, but it should be noted

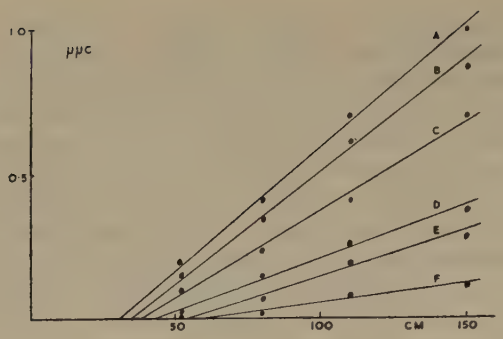

Figure 6. The charge released by the splashing of drops of different mass as a function of the height from which released for a constant field of 6,600 v m^{-1}. A, 100·6 mg; B, 80·3 mg; C, 52·6 mg; D, 33·2 mg; E, 21·0 mg; F, 10·7 mg.

that there is a height, different for each size of drop, below which no charge is released. Observation showed these to be the heights below which the drops did not splash. The corresponding velocities are small and may be neglected when considering drops falling at their terminal velocities. The variation with mass is also linear.

As the dependence of the released charge on the field could be examined in one series of observations, use was made of a harder target, obtained by arranging the brass disc with a thinner covering of water. In Fig. 7, which shows the result of this experiment, a linear dependence is apparent. The charges are about five times those for the softer target.

It should be noted that according to Nolan and Enright (1922) the Lenard effect for these drops should release a charge of 3 $\mu\mu$C per drop in the absence of a field. The absence of such a charge in Fig. 7 does not preclude the Lenard effect, for, as Nolan and Enright pointed out, the electrification becomes much smaller if the shattering of the drop is less violent (they used an air blast) and if the water is not pure. However, its absence would appear to support Gill and Alfrey's contention.

All these results may be summarized by stating that when drops splash, the charge released is directly proportional to the product of the field and the energy dissipated in the splash.

(*c*) *Discussion of possible processes*

There are three mechanisms by which the charge could be released.

(1) *Spark process* : While falling, the drop is polarized by the field. On approaching the target, large fields will occur between the base of the drop and the target. When the drop is sufficiently near the target the air will break down and there will be a spark.

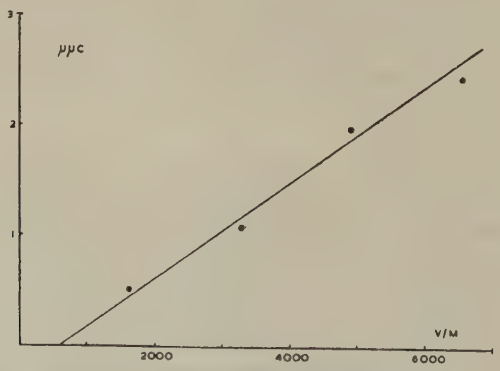

Figure 7. The charge released by 80·3 mg drops falling 80 cm shown as a function of field.

Some of the ions produced in the spark will escape the impact and be available for conduction.

(2) *Splash process. Point discharge.* After impact, splash will occur. Fragments will be projected off the target at various angles depending on the size and velocity of the drop, and on the nature of the target. These will, for a time, remain joined to the target by thin films and filaments of water. The sharp edges presented to the field by these fragments will cause convergence of the field and point discharge will occur.

(3) *Splash process. Breaking of films.* After impact, splash will occur. Fragments will be projected off the target at various angles depending on the size and velocity of the drop, and on the nature of the target. These will, for a time, remain joined to the target by thin films and filaments which will carry large induced charges. It is well known that as films collapse, very small droplets are left suspended in the air. (See, for example, Knelman, Dombrowski and Newitt 1954). In the present case these will be charged and will therefore behave like ions.

In order to indicate the nature of the process, uncharged ball bearings were dropped on the target in place of water drops. It was found that no charge was released when they fell on a dry target. This eliminated the spark process. It was also found that no charge was released when they fell on a wet target unless they bounced off, or rolled off sufficiently fast to scatter water as they did so. It therefore became clear that one of the splash processes was responsible for the release of charge, and we may readily distinguish which, by recalling the linear relationship between the released charge and the field. This is not consistent with a point discharge process which would give a square-law relation in the absence of wind. (A change of field will not alter the geometry of the splash). If we suppose that 0·1 cm^2 of the film contributes to the fragments left in the air after each splash, and that the field is 4,000 v m^{-1}, then we have 0·4 $\mu\mu$C released by each drop. This is similar to the charges found experimentally. We may therefore conclude that the disintegration of films of water in the splash is responsible for the release of charge.

(*d*) *Nature of the ions*

The ' ions ' presumably consist of extremely small water droplets or groups of water molecules carrying a charge. Some indication of the mobilities of the ions involved in the measured currents can be obtained from the speed of response of the current at the start and finish of a period of splashing. Although the rise and fall of the current was rapid, there was a suggestion of a component taking about three minutes to build up or die away, implying the presence of some ions with mobilities as low as 10^{-3} cm sec^{-1}/v cm^{-1}. The greater part of the current, however, appeared to be carried by ions of high mobility.

(*e*) *The process in the atmosphere*

The consequences of the release of charge will be discussed more fully in § 4, but before going further, it is helpful to work out the rate at which charge is released from the ground as a function of field and rainfall.

It is difficult to estimate the ease with which splash occurs on a natural surface, but the harder surface used in the determination of the field dependence (Fig. 7) is probably not untypical. We may therefore take the charge released by an 80·3 mg drop falling from 80 cm and splashing in a field E v m^{-1} as $-\ 3{\cdot}8\ 10^{-4}\ E$ $\mu\mu$C. The energy of these drops on hitting the target was $6{\cdot}31\ 10^3$ ergs. The energy of a 1 mg drop at its terminal velocity is $1{\cdot}13\ 10^2$ ergs. Hence the charge released by a 1 mg drop at its terminal velocity is

$$-\ 6{\cdot}8\ 10^{-6}\ E \qquad \mu\mu\text{C}$$

Now in the range 1-100 mg the terminal velocity of drops varies roughly as the 1/6th power of the mass, so that the charge released by a drop of mass m mg is

$$-\ 6{\cdot}8\ m^{1{\cdot}33}\ 10^{-6}\ E \qquad \mu\mu\text{C}$$

If all the drops were of the same size the rate at which they would fall is

$$1{\cdot}67\ 10^4\ R\ m^{-1} \qquad \text{drops m}^{-2}\ \text{min}^{-1}$$

where R is the rate of rainfall in mm hr^{-1}. Therefore, if all were of the same size, the charge released would be

$$-\ 0{\cdot}114\ m^{0{\cdot}33}\ R\ E \qquad \mu\mu\text{C m}^{-2}\ \text{min}^{-1}$$

and if the mass spectrum as a function of drop diameter is $M(d)$, the total charge released would be

$$-\ 0{\cdot}114\ R\ E \int_0^\infty m^{0{\cdot}33}\ M(d)\ dd \qquad \mu\mu\text{C m}^{-2}\ \text{min}^{-1}$$

Now in his analysis of raindrop sizes, Best (1950) gives

$$F = 1 - \exp\left[-(d/a)^n\right]$$

and $$a = A\ R^p$$

where F = the fraction of the mass of water in a given volume of air which is made up of drops of diameter less than d mm

$$A = 1{\cdot}3$$

and $$p = 0{\cdot}232$$

n varies with the type of rain, but Best gives as an average value

$$n = 2{\cdot}25$$

The water-drop mass spectrum in a given volume of air as a function of drop diameter is therefore (omitting constants)

$$\frac{dF}{dd} = d^{n-1} \exp\left[-(d/a)^n\right]$$

so that the water-drop mass spectrum reaching the ground is

$$M(d) = d^{n-\frac{1}{2}} \exp\left[-(d/a)^n\right]$$

The integrand therefore becomes

$$d^{n+\frac{1}{2}} \exp\left[-(d/a)^n\right]$$

We can take the condition that this be a maximum as defining the value of the effective mean diameter. This gives

$$\bar{d} = a\,(1 + 1/2n)^{1/n} = 1{\cdot}42\ R^{0{\cdot}232}$$

so that $$\overline{m^{0{\cdot}33}} = 1{\cdot}42\ (\pi/6)^{0{\cdot}33}\ R^{0{\cdot}232}$$

Therefore the total rate of release of charge by rain is

$$\frac{d\sigma}{dt} = -\ 0{\cdot}13\ R^{1{\cdot}23}\ E \qquad \mu\mu\text{C m}^{-2}\ \text{min}^{-1}$$

This expression probably fails in the lowest rates of rainfall as it is likely that some of the smallest drops are not large enough to splash, but it should provide a reasonable indication of the effects accompanying heavier rain.

3. The space charge near the ground

(*a*) *The nature of the experiments*

The previous experiments required an immediate investigation of the behaviour of the space charge near the ground, and for this purpose an apparatus was developed similar to that used by Obolensky and Brown (Brown 1930), but the charge removed from the air by the steel-wool filter was measured continuously with a vibrating-reed electrometer. In this way, on the less sensitive range used during disturbed weather, a time constant of about one second was achieved. Again, elaborate precautions were taken to safeguard the reliability of the measurements in all weather conditions, and careful electrical screening prevented the interference of external fields. During this series of measurements records were also made of all the variables observed during the work of § 1.

(*b*) *The space charge in undisturbed conditions*

Even in fine weather, large fluctuations were often found to occur in the space charge, changes of sign not being uncommon. This makes difficult the estimation of the mean fine weather value, but this is probably about $+ 2\ \mu\mu C\ m^{-3}$. Considerable space charge, usually negative in sign, seemed sometimes to be associated with mist. Values of about $- 100\ \mu\mu C\ m^{-3}$ (or 600 electronic charges per cubic centimetre) have been recorded. The field usually remained positive.

On several occasions close similarities were observed between the variations of the field and space charge. No associated changes were apparent in the small-ion concentration. In all cases the similarities correspond to the passage of charge near the ground, and two classes of effect could be distinguished.

(1) Small and intense clouds of positive charge giving rise to short positive deviations in the field were found to be associated with smoky exhaust from passing traffic, and

(2) The field and space charge showed close correspondence in changes which were often gradual and sometimes had a characteristic duration of over an hour. On these occasions the field was usually low (rarely more than $100\ v\ m^{-1}$) and the atmospheric conditions quiet. The effect, which sometimes continued for many hours, may be associated with particularly stable conditions as it occurred more often during the night. Fig. 8 gives an example of this. The figures below the field record are the heights in metres to which the observed changes of space charge would have to persist to account for the corresponding changes of field. Values of up to 100 m were found on other occasions when there was less similarity to distinct clouds of charge, but it was clear that the charges responsible are usually confined to within a few tens of metres of the ground, presumably by the stable conditions. It was noted that whenever the records gave the appearance of distinct clouds of charge, such clouds were always negative, suggesting overhead power cables as a possible origin of the charge.

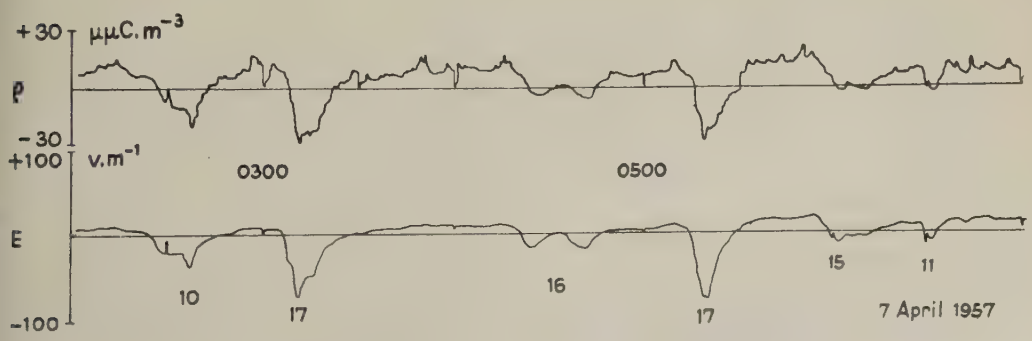

Figure 8. Correlation of the field and space charge.

(c) *The space charge in disturbed conditions*

In disturbed conditions, four processes can be distinguished :

(1) In electric fields of up to some 600 v m^{-1} the space charge is found to be subject to small changes in the same sense as the field. The size of the changes is similar to that which is to be expected from the electrode effect (i.e., up to 40 $\mu\mu C\ m^{-3}$).

(2) In larger fields, natural point discharge is found to give rise to considerable space charge of sign opposite to that of the field.

Fig. 9 shows such an occasion. During the first period of intense negative field, when a little rain fell with a negligible production of ions, point discharge caused the accumulation of space charge near the ground at a rate of 200 $\mu\mu C\ m^{-3}\ min^{-1}$ until a value of more than 600 $\mu\mu C\ m^{-3}$ was reached. Under these conditions the field will double within some tens of metres of the ground. During the second, less intense period of negative field, positive space charge again accumulates, but more slowly. The absence of any increase in the concentration of small ions on these occasions shows that, by the time the charge reaches the ground, it is all on ions of low mobility. As it reaches the ground by turbulence, the response of the space charge to changes in the field is not immediate, and large fields must persist for some minutes before large densities occur.

(3) In the presence of heavy rain ions released at the ground by splashing can give rise to large space charge in a very short time. Unlike that arising from point discharge, this charge is initially concentrated near the ground and densities of 1,000 $\mu\mu C\ m^{-3}$ can easily occur. When considerable point discharge takes place, the charge released by splashing makes a significant contribution to the observed space charge only when the rain is moderately heavy.

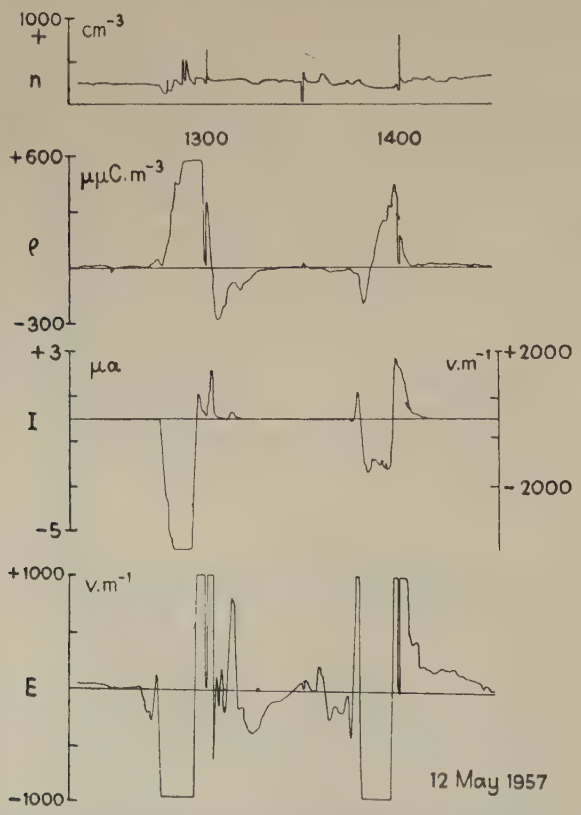

Figure 9. Space charge resulting from point discharge. Simultaneous records of positive small-ion concentration, space charge, point discharge current and field.

Fig. 10 shows a simple example of charge produced by the splashing of rain. During the period of negative field, a short shower took place. The sudden rise in the space charge coincides exactly with the production of small ions. (The peaks on the space-charge record at 1330 and 1400 are instrumental). Exact comparison of the records is difficult, but during the latter part of the peak the ion concentration was just over 2,000 cm^{-3} or about 850 $\mu\mu C\ m^{-3}$, which is a little smaller than the observed space charge. We may conclude, by comparison in this simple case, that by far the greater part of the charge released by splashing is carried by particles of the mobility of small ions.

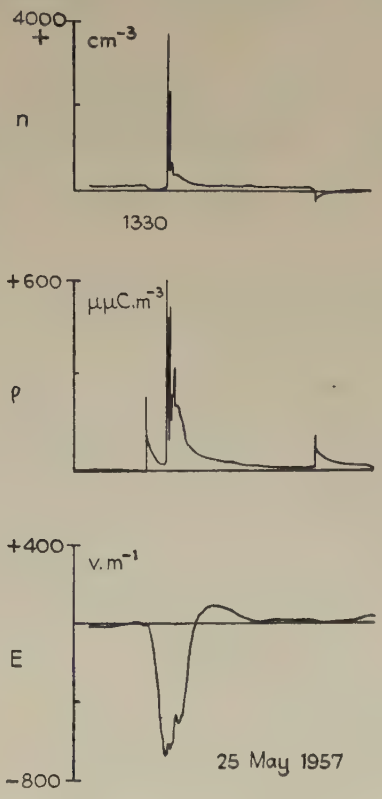

Figure 10. The production of charge by the splashing of rain. Simultaneous records of positive small-ion concentration, space charge and field.

During periods of prolonged rain, the behaviour was essentially similar, the space charge sometimes building up to give field gradients of over 100 v m^{-2} at the ground. Remembering that within a period of minutes these charges would become mixed to a height of many metres, it is certain that the fields observed at the ground were often considerably smaller than the ' free ' field well above the surface.

(4) Regions of high space charge are sometimes found in association with a column of rain and these appear to control the field.

The space charge arising from the last three processes can be sufficiently great seriously to modify the measured fields. To summarize we may therefore say that in all weather conditions field measurements made at the ground may be seriously affected by space charge near the ground. In none of these measurements was there found any evidence of a field-independent release of charge by splashing as is required by the Lenard effect.

4. Discussion

(a) *The electrical state in steady rain*

If we suppose that steady rain takes place from a uniform cloud layer of considerable horizontal extent, observed fields will correspond to the total charge above the observer, and changes in the field will be associated with current to ground. Now in steady rain, the currents due to conduction, splashing and convection by the rain, are all large in comparison with the potential gradient. That is to say, that within a few minutes, any one of these acting alone would produce a large change in the potential gradient. It is therefore not unreasonable to consider the problem as one in which there is near current equilibrium.

The current to ground is made up of

(i) Rain current

$$I_r = 16{\cdot}7\, R\, q \qquad \mu\mu\text{C m}^{-2}\ \text{min}^{-1}$$

where q $\mu\mu$C m^{-3} is the charge on the rain and includes any currents due to the Lenard effect if this does take place.

(ii) Conduction current

$$I_c = 60\, \lambda\, E = 1{\cdot}1\, E \qquad \mu\mu\text{C m}^{-2}\ \text{min}^{-1}$$

$$(\text{taking } \lambda = 1{\cdot}8 \times 10^{-14}\ \text{ohm}^{-1}\ \text{m}^{-1})$$

(iii) Current from splashing. (§ 2 (e))

$$I_s = 0{\cdot}13\, R^{1{\cdot}23}\, E \qquad \mu\mu\text{C m}^{-2}\ \text{min}^{-1}$$

It is possible that the small drops associated with very light rain may be too small to splash, but we introduce no great error in including this term as in light rain it becomes very much smaller than that due to conduction.

As the first approximation to a steady state, we can put the total current to the ground as zero, giving

$$q = -\frac{E}{16{\cdot}7\, R}(1{\cdot}1 + 0{\cdot}13\, R^{1{\cdot}23})$$

If we take $R = 2$ for light rain this becomes

$$q = -\,0{\cdot}042\, E$$

which can be compared to the Simpson (1949) formula

$$q = -\,0{\cdot}048\,(E - 400)$$

In this context Simpson's constant term must be thought of as a *current* to earth. With insufficient data as regards the electrical state of the clouds, we cannot calculate what current will flow to earth from the equipotential regions high in the atmosphere during the rain, but we may obtain an indication of the effect of such a current by assuming that in the steady state there flows to earth a current equal to that of fine weather. We then have

$$q = -\,0{\cdot}042\,(E - 105)$$

In these calculations values of conductivity and fine-weather current have been taken for a typical land station (see Chalmers 1957), so that Simpson's constants are not to be expected. Substitution of the Kew values is not helpful as it is not known for how great a height the parameters have the values which are so peculiar to Kew.

In his measurements of the total current, Chalmers (1956) obtains a non-constant value

$$I_t = -\,0{\cdot}71\,(E - 150)$$

This may be because the surface he uses is not strictly typical, but it should be noted that

if his results are corrected for conduction current and splashing, they can be written

$$I_r = -2{\cdot}1\,(E - 50)$$

which can be compared with the Simpson formula in the same form

$$I_r = -1{\cdot}6\,(E - 400) \quad (\text{taking } R = 2)$$

It seems that here we may be very close to the true explanation of these results, but before it will be possible to decide finally, it will be necessary to obtain more data regarding the electrical state of clouds giving steady precipitation.

(*b*) *Field measurements in heavy rain*

In heavy rain the current due to splashing (§ 2, (e)) becomes large, and the consequent rate of change of field near the ground may be written

$$\frac{dE}{dt} = \frac{dX}{dt} - 0{\cdot}015\,R^{1{\cdot}23}\,E \qquad \text{v m}^{-1}\,\text{min}^{-1}$$

where $\frac{dX}{dt}$ is the rate of change of the free potential gradient. Any field will therefore be reduced towards zero with a time constant of $66{\cdot}7\,R^{-1{\cdot}23}$ minutes. If we take $R = 15$ as being typical of a heavy shower, the time constant is only 2·5 min. It is therefore clear that large fields cannot *persist* at the ground during heavy rain. In fact, large fields can only *occur* when $\frac{dX}{dt}$ is large as happens, for instance, with active cumulonimbus. This is fully in accord with observation.

It is also well known that large field changes often take place in a few seconds during heavy rain, and in the absence of lightning their rapidity can only be explained in terms of charges of considerable magnitude near the ground. The presence of such charges is easily understood in terms of charge released by splashing, particularly when it is remembered that, until diluted with surrounding air, such clouds of charge will produce field changes at the ground of the same order of magnitude as the field which caused their creation. Charge from point discharge will also be important in this respect, although at the ground its effects will be less violent as some mixing will have taken place before it reaches the surface. The effects of these clouds of charge have already been noted by Lutz (1941) and Hutchinson (1951) who found that point discharge currents and field changes were not strictly equivalent in periods of rapid change, and Whitlock and Chalmers (1956) describe marked changes in the field patterns recorded at different places along the paths of individual storms. In particular, their results show the most violent modifications in the region of rainfall and they also note that the simple V field pattern of the lighter showers is often turned into a W pattern in the heaviest rain. These facts are readily understood in the light of the present work.

The release of charge by splashing may also account, at least in part, for the presence of the positive charge in association with the area of heavy rain in the thunderstorm, for the manner of the breaking of the drops in the rain column itself (Lane and Green 1956) is such as to release positive charge to be left in the air while the larger-drop fragments carry away the negative charge. This will at least *reduce* the field in this region.

(*c*) *The early alti-electrograph results*

In the alti-electrograph measurements of Simpson and Scrase (1937) their rough field-calibration was obtained by comparison of the field at the ground with the start of the electrograph trace at the beginning of some ascents. The laboratory measurements by which Chapman (1956) obtained a recalibration of his apparatus to give fields of up to

230,000 v m^{-1} in the cloud cannot, therefore, explain the low fields apparently found by Simpson and Scrase and some other explanation has to be found. Such an explanation is provided in terms of charges present near the ground.

Wilson (1925) assumed that the small ions which initially carry the charge from point discharge will retain their high mobilities. This will not be so. Like other small ions, they will be lost within some 30 sec of their creation and, except inasmuch as it is prevented by mixing or large-scale convection, their charge, virtually immobilized on large ions, will remain concentrated within some tens of metres of the ground. The gradual increase in field to the cloud base predicted by Wilson will therefore virtually be absent and there will be a rapid increase in field near the ground. This effect will be accentuated by any charge released by rain and, as shown in § 3, sufficient charge densities can occur for the field to increase manifold within some tens of metres of the ground. Now because of the length of the trailing wire, the electrograph did not begin to record until reaching a height of some 30 m and the resolution of the trace would be limited to some tens of metres. Consequently, the instrument must have reached a considerable height before comparison of the trace with the field at the ground became possible, so that the comparison would have been in error by some large factor, perhaps by as much as an order of magnitude. Such a factor would bring the early measurements into agreement with the work of Gunn (1948) and Chapman (1956).

Conclusions

It is evident from the work described in this paper that measurements of the electric field near the ground can be modified seriously by the presence of space charge in all weather conditions, and it is clear that, particularly in disturbed weather, we must exercise the utmost caution in interpreting measurements of the potential gradient near the ground.

Acknowledgments

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Practical field instruments for estimation of radiation and of evaporation

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(Manuscript received 17 November 1958)

Summary

A distillation instrument for the integration of radiation, described by Bellani in 1836, rebuilt in modern materials by Gunn, Kirk and Waterhouse (1945), has a thermal efficiency of over 75 per cent. The improved instrument, mounted at ground level in East Africa, with the condenser underground in constant cool conditions, had a performance that justified manufacture. Comparisons of the manufactured instruments with a Kipp solarimeter gave high linear correlations. These results show the distillation instruments, when so calibrated, to be useful for field estimations of solar radiation. Their cost is low and the daily estimate of total radiation is quickly obtained from a simple burette reading.

Ten years' data for these Gunn-Bellani integrators are compared with those from 4 ft diameter open water pans. A mounting is described for these pans in shallow revetted pits where their sides are shielded from the sun and are insulated from the soil by an air space. A linear correlation based on 164 ten-day means accounts for 85 per cent of the variability. It appears that in the high-altitude tropics this radiation integrator by itself can give the basic data for adequate estimate of water use by vegetation, and for control of irrigation.

1. Development of a liquid-distillation instrument as a radiation integrator

The principle of a radiation meter integrating insolation by a distillation process was evolved by Bellani (1836) and various modifications of his intrument have remained in use on the continent of Europe and in the Belgian Congo, e.g., Regnier (1947). These devices have been constructed entirely of glass, and hence have very variable thermal efficiency. Prohaska and Wierzejewski (1947) showed that, as a result of the poor conductivity of the glass bulb containing liquid, efficiency fell from 60 per cent to 30 per cent as distillation progressed. Mörikofer (1937) at Davos Observatory achieved considerable improvement in this respect by covering the inner glass bulb with sputtered copper. Courvoisier and Wierzejewski (1958) have subsequently added a coating of chromium to attain a constant efficiency of 40 per cent. In field use, however, the metal-glass contact deteriorates rather rapidly.

Modern techniques of sealing metal to glass make possible a great improvement in thermal efficiency by substituting a thin-walled blackened copper sphere for the internal glass bulb. Instruments of this type were first produced by Gunn, Kirk and Waterhouse (1945). Calibration in the tropics by Gunn and Yeo (1951) gave an efficiency of over 75 per cent with no change in this efficiency as distillation proceeded. Other improvements were the separate evacuation of the inner distillation system and of the outer envelope, and the incorporation of a copper-walled section into the glass condenser.

2. Mounting for field use

Bellani, Mörikofer and others, suspended their instruments with both radiation-receiver and condensing burette in full sunlight. Used in this way the condenser temperature is subject to wide fluctuation. Gunn, Kirk and Waterhouse reduced the fluctuations by protecting the condenser from sunlight with a light metal shield.

In 1947 the author obtained two of the original prototype Gunn-Bellani instruments, filled with alcohol and water respectively, for studies of evaporation and crop-water use in the high-altitude tropics of East Africa. To improve the efficiency of the distillation the condenser was placed below ground level, and was thus provided with a cooler and more constant environment than that obtained by previous workers.

Details and dimensions of the mounting are given in Fig. 1. The top of the copper bulb is at ground level while the shallow projecting rim of the mounting serves to cut off ground reflection while protecting the envelope from loose soil and rain splash. A rubber diaphragm in the form of an inverted cone guides the burette to a hole at its apex, while the glass envelope rests on a rubber seating. These features are important for ease and speed of handling in the field and have enabled junior African recording staff with very limited training and experience to take daily readings from 1947 to 1958 without damage to the instrument, which is still in use.

The water-filled type is read daily at 08 hr; the 36 m li of water it contains is just sufficient for a full day's run near the equator. The daily integration of short-wave solar radiation at ground level by this means avoids the complications discussed by Gunn *et al.* for the briefer runs used during their study of locusts.

3. Manufacture of the Gunn-Bellani radiometer

For the first eight years of observations no standard radiation thermopile was available in East Africa for calibration purposes, but consistently useful relationships were observed between daily distillation values and the evaporation from open water tanks (Pereira 1955). Arrangements were therefore made for manufacture in the United Kingdom by Messrs. Baird and Tatlock (London) Ltd. With the collaboration of Sir Bernard Keen, three modifications, based on field experience, were incorporated in the production design. These were the addition of fins to the copper section of the condenser, the addition of struts to support the heavy water-filled copper bulb on its glass stem, and the increase in the volume of water from 36 m li to 42 m li to permit daily runs at higher latitudes. Although it increases distillation efficiency, the copper section is not essential when the condenser is placed underground, and without it the instrument is cheaper and more robust. Manufacture of alternative models, with and without the condenser, was therefore arranged. (See Fig. 2, Plate I). The first manufactured instruments were received for test in 1956.

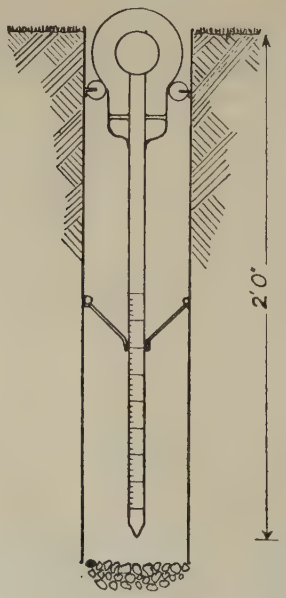
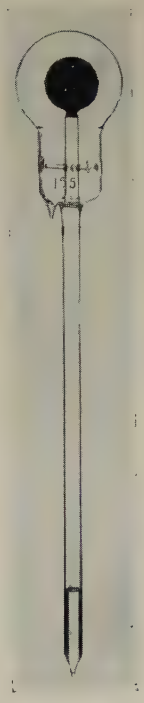
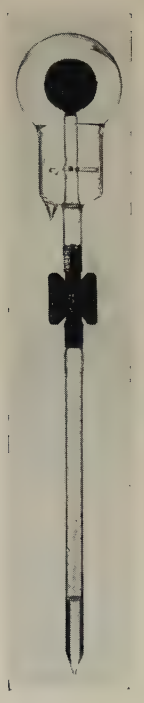


Figure 1. Mounting for radiation integrator. The mounting cylinder is of 5 in. internal diameter and projects half an inch above soil level. The top of the copper bulb is at soil level. Grass is clipped short to the level of the cylinder.



(a)



(b)

Figure 2. Alternative patterns of Gunn-Bellani instruments.

4. Calibration with the Kipp solarimeter

For calibration of the new instruments the East African Meteorological Department kindly lent a Kipp thermopile of the Moll type, which had been standardized at the Pretoria Observatory in preparation for the International Geophysical Year. The Kipp instrument was used at Muguga (6,800 ft a.s.l., 80 mi S of the Equator) with a Cambridge recording galvanometer.

(*a*) *Comparison of instruments*

Both thermopile and distillation radiometer receive only short-wave radiation passing through their glass envelopes. The former has a flat receiving surface, but its second glass hemisphere incurs an additional loss in efficiency of some 8 per cent. The spherical receiver of the Gunn-Bellani instrument within its single spherical envelope minimizes reflection and refraction losses.

The side walls of the mounting cylinder, projecting above ground, are necessary to protect the blackened sphere from radiation reflected from the soil or grass, but at the same time cut off sun and sky radiation for the first 10° above the horizon. This cut-off is usually of little consequence since radiation intensities are then very low. The reception of radiation on a spherical surface in lieu of a plane area causes a maximum difference at low elevations of the sun, and is therefore minimized in the tropical latitudes in which the observations here reported have been made. In their study of the Campbell-Stokes sunshine recorder Glover and McCulloch (1958) found the errors due to the geometry of the spherical receiver to be self-compensating when summed over whole days.

Trickett, Moulsley and Edwards (1957) attempted to obtain a plane receiving area by using a hemispherical receiver with the upper surface horizontal. The edge effects of the hemisphere, however, complicate the reception of low-angle insolation over the elevation range within which the spherical receiver also departs most from the horizontal model.

(*b*) *Results of calibration*

During six months (27 May 1957 to 28 Nov. 1957) of consecutive daily readings, in which the Kipp solarimeter recorded daily radiation totals (R) from 90 to 790 g cal cm^{-2} in the tropical 12-hr day, sample instruments gave the following relationships, where d is the daily distillation in m li. The square of the correlation coefficient r is included to indicate the proportion of the variance accounted for by the linear regression.

TABLE 1. Calibration in radiation units

	R	r^2	r	n
Original prototype, with plain copper condenser (after 10 years of daily use)				
No. 0	$42 + 32\,d$	0·90	0·950	160
Production models with plain-glass condenser				
No. 2	$132 + 36\,d$	0·94	0·970	161
Production models with finned-copper condensers				
No. 10	$126 + 32\,d$	0·91	0·954	83
No. 13	$131 + 33\,d$	0·98	0·990	28
No. 25	$155 + 40\,d$	0·95	0·975	158

The data for instruments Nos. 2 and 25 are plotted in Fig. 3. No consistent advantage was obtained from the use of copper condensers, and indeed since the glass condenser model accounts for all but 6 per cent of the variance, there is little to be expected. While the all-glass instrument is indicated for field use, the more elaborate model will be further studied.

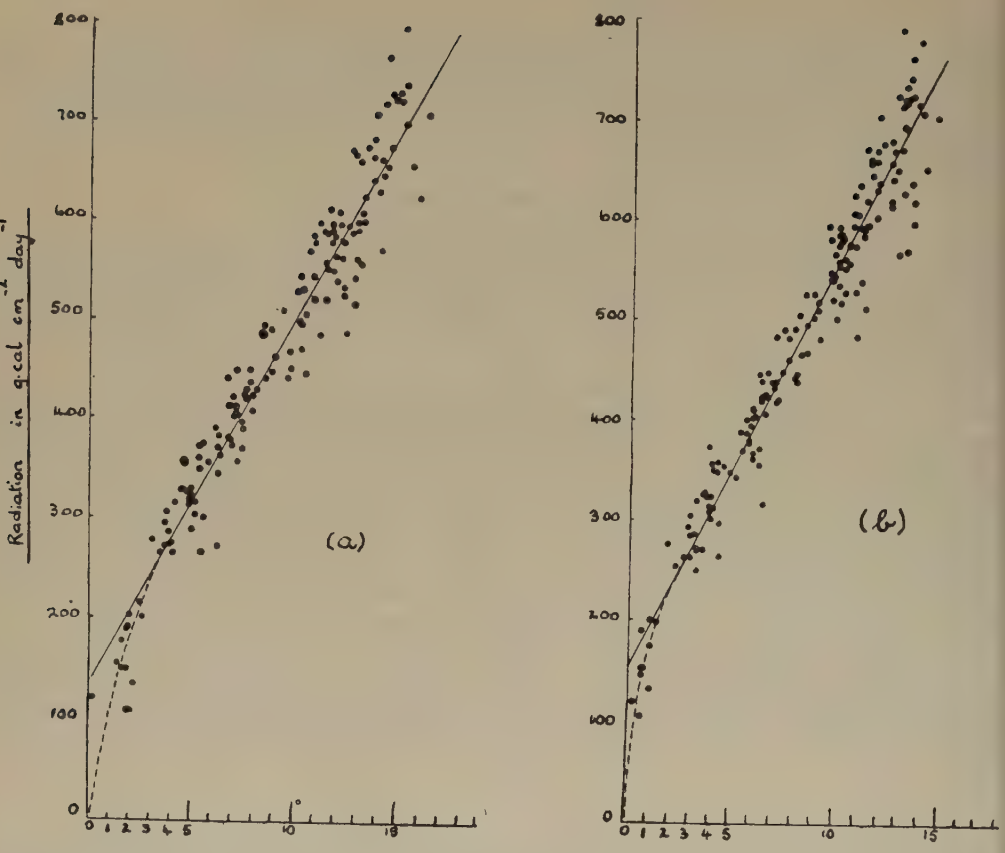


Figure 3 (a) and (b). Daily distillation in m li of water. Calibration of manufactured instruments with Kipp Solarimeter at 6,000 ft a.s.l., 1° 13′S, 36° 38′E.

(a) model with plain glass condenser. (b) model with copper-finned condenser.

The increase in the quantity of water in the instrument (from 36 to 42 m li), although necessary to provide for days of maximum insolation, has had the rather undesirable effect of raising the threshold value of the linear relationship with the solarimeter from 42 g cal cm^{-2} day^{-1} in the prototype model by Gunn *et al.* to an average of nearly 130 in the production models. Fig. 3 shows that the linear relationship no longer holds below about 175 g cal cm^{-2}, the curve falling off rapidly towards zero. While this is of little consequence under tropical or temperate-summer conditions (in which energy estimates are in greatest demand for irrigation and other development purposes) it eliminates the use of these instruments for high-latitude winter conditions. For these conditions a more volatile liquid, not liable to freeze, has obvious advantages. Some of the instruments built by Gunn, Kirk and Waterhouse contained methyl alcohol and the properties of suitable liquids have been discussed by Trickett, Moulsley and Edwards (1957). The total thermal capacity of the instrument is then very low, so that daily runs can be obtained only in a limited range of insolation conditions. It appears improbable that demand for use of field instruments in such conditions will warrant the manufacture of alcohol-filled models.

The good agreement with the Kipp solarimeter under tropical conditions shows the simple and inexpensive Gunn-Bellani radiometers to have practical application over wide areas in which facilities for operation of recording galvanometers do not exist.

(c) *Seasonal variation in daily radiation values near Nairobi*

The only radiation data previously published for East Africa were taken by the East African Meteorological Department using a Kipp-Moll instrument with recording galvanometer. This instrument was used at the Kabete Station from March 1938 to April 1943 at an altitude of 5,800 ft. For the approximately constant day length at this latitude (1·3°S) a 5-yr mean value of 507 g cal cm^{-2} day^{-1} was recorded.

The prototype distillation instrument was operated for the years 1953-1958 at Muguga, 10 mi away and of 1,000 ft greater altitude. The 6-yr mean value observed was 499 g cal cm^{-2} day^{-1}. The monthly means for daily radiation totals together with the equivalent energy values expressed as monthly totals for the evaporation of water are given in Table 2. It is clear that, under the conditions tested, the distillation instrument gives a good account of radiation.

TABLE 2. MONTHLY MEANS OF DAILY RADIATION VALUES AT THE SOIL SURFACE

(a) As g cal cm^{-2} day^{-1} (of approx. 12 hr), (b) Energy equivalent as inches of water evaporated per month.

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Per annum
1938-1943 at 5,800 ft a.s.l. (From Kipp-Moll solarimeter)													
(a)	628	627	594	524	447	376	349	373	518	547	526	575	507
(b)	13·0	11·7	12·3	10·8	9·2	7·5	7·2	7·7	10·4	11·3	10·5	11·9	123·5
1953-1958 at 6,800 ft a.s.l. (From Gunn-Bellani radiation integrator)													
(a)	585	612	612	497	420	389	365	389	509	548	501	562	499
(b)	12·1	11·4	12·7	9·9	8·7	7·8	7·5	8·0	10·2	11·3	10·0	11·6	121

In 1957 Kipp-Moll solarimeters with recording galvanometers were operated both by the East African Meteorological Department at Nairobi (5,400 ft) and, 15 mi away, by East African Agriculture and Forestry Research Organization at Muguga (6,800 ft). The annual means for daily values were 471·5 and 472·3 g cal cm^{-2} day^{-1} respectively. Although this exact agreement is somewhat fortuitous it does appear that, in spite of short-term variability of cloud cover, the annual totals of radiation reaching the ground do not vary much within a few miles.

5. DIRECT MEASUREMENT OF EVAPORATION FROM OPEN WATER

In semi-arid parts of the world the rates of water loss from reservoirs and from irrigated crops are usually of more immediate interest than are the radiation values. Open-water evaporation measurements are, however, difficult to standardize. Evaporation pans in current use exhibit many arbitrary differences in dimensions and in manner of exposure, which often invalidate comparisons of results.

Cummings (1940) designed an open-water tank with elaborate thermal insulation of rock wool and porous concrete as an integrator of total daily solar radiation; this was employed in the extensive inter-agency co-operative Water-Loss Investigations of Lake Hefner (1952). Harbeck (1952) reporting on the Cummings device, concluded that ' For the purposes of computing evaporation, using the energy-budget technique, the instrument appears to be a satisfactory substitute for the flat-plate radiometer and pyrheliometers.' Most of the effects of the massive construction of the Cummings tank can be achieved much more cheaply and conveniently by a mounting employing the soil for shielding and an air gap for insulation from diurnal soil-temperature fluctuations.

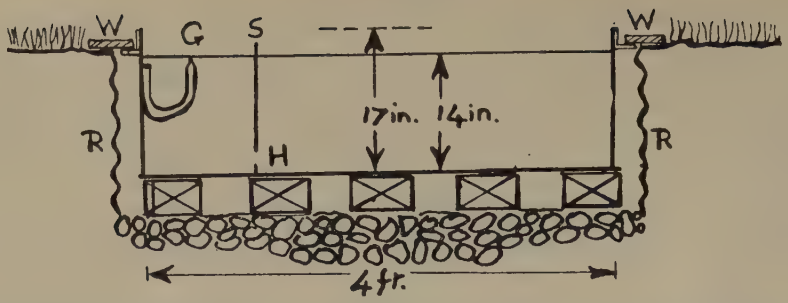


Figure 4. Mounting for evaporation pan. R – Revetment, a circular hoop of corrugated galvanised iron; W – Wooden cover, in sections for ease of handling; G – Hook gauge; H – Holes to equalise water level; S – Shield for hook gauge.

Under tropical conditions, pans exposed above ground are excessively heated, while pans buried in contact with the soil suffer rapid corrosion and are difficult to check for suspected leakage. When leakage is discovered there is serious uncertainty as to how long a run of data has been affected. Practical requirements are thus protection of the sides from the sun, protection from soil contact, and ease of inspection. A form of mounting incorporating these features (Pereira 1948) has proved very satisfactory in the field and is illustrated in Fig. 4.

6. Estimation of open-water evaporation by the Gunn-Bellani radiometer

Evaporation pans in this form of mounting have been used by the author at altitudes of 5,400, 5,800 and 6,800 ft successively, over the 10 years 1948 to 1957 with comparative observations of a Gunn-Bellani radiation integrator, mounted as described above. For the last 18 months the pan has also been compared with the Kipp solarimeter.

Hutchinson and Farbrother (1956) have shown, by the use of an autographic water-level recorder, that splash losses from an evaporation tank can be a serious source of error under tropical rainfall intensities. The operation of such tanks or pans also requires closer and more critical supervision than is readily available in most parts of Africa. In order to maintain a clear water surface under dusty dry-season conditions and with a high insect population, it is necessary to remove debris daily, to change the water every 4 to 5 weeks, and also to remove surface contamination at least weekly. Small but unavoidable changes in water-temperature result. Hence, in comparing the Gunn-Bellani or Kipp instrument with the evaporation tanks, a substantial part of the discrepancies may be ascribed to the splash losses and other difficulties of operation of the tanks.

(a) Comparison of sunken insulated tank with Kipp solarimeter

Heat storage changes in evaporation tanks render daily values uncertain; the comparisons are therefore made in 10-day means. Daily values are given to illustrate this variability. Both evaporation E_0 and radiation R are given in inches of water per day. At Muguga, 10-day means (28 May 1957 to 28 Nov. 1957)

$$E_0 = 0{\cdot}74\,R - 0{\cdot}073 \qquad r^2 = 0{\cdot}92 \qquad r = 0{\cdot}959$$

while for daily values

$$E_0 = 0{\cdot}58\,R - 0{\cdot}020 \qquad r^2 = 0{\cdot}74 \qquad r = 0{\cdot}860$$

Thus although the solarimeter cannot register through its double glass envelope the longer wave-lengths which carry a little of the heat energy used in evaporation, it can still account under East African conditions for 92 per cent of the variance by a linear relationship.

(b) Comparison of sunken insulated tank and Gunn-Bellani radiometer

For comparison with the foregoing equations, the relationships are first given for the same six-month period, followed by the long-term observations of the prototype model. Mean daily distillation d in m li; mean daily evaporation E_0 in inches.

Six months' comparisons with new models

At Muguga, 10-day means 28 May 1957 to 28 Nov. 1957

Production model with plain glass condenser

$$E_0 = 0{\cdot}018\,d - 0{\cdot}009 \qquad r^2 = 0{\cdot}94 \qquad r = 0{\cdot}970$$

Production model with copper condenser

$$E_0 = 0{\cdot}020\,d - 0{\cdot}003 \qquad r^2 = 0{\cdot}95 \qquad r = 0{\cdot}976$$

These linear relationships pass close to the origin and compare well with that of the Kipp solarimeter over the same period.

Original prototype model

$$E_0 = 0{\cdot}17\,d - 0{\cdot}07 \qquad r^2 = 0{\cdot}89 \qquad r = 0{\cdot}944$$

Long-term comparison with original prototype model

At Muguga (6,800 ft a.s.l.) for 1,060 days in 10-day means

$$E_0 = 0{\cdot}015\,d - 0{\cdot}05 \qquad r^2 = 0{\cdot}86 \qquad r = 0{\cdot}930$$

At Ruiru (5,400 ft a.s.l.) for 580 days in 10-day means

$$E_0 = 0{\cdot}012\,d - 0{\cdot}025 \qquad r^2 = 0{\cdot}85 \qquad r = 0{\cdot}923$$

While exaggerated evaporation values due to splash losses from major storms can readily be detected and have already been eliminated from the above data, a substantial part is still played by splash losses in the 15 per cent of the variability not accounted for by the long-term linear regressions. This can be illustrated from the Ruiru data as follows :

No. of 10-day periods	Rain falling during period	Correlation of E_0 and d	
		r^2	r
23	> 1·00 in.	0·74	0·858
19	> 0·10, < 1·00 in.	0·87	0·935
16	< 0·10 in.	0·93	0·963

At the higher altitude of Muguga, rainfall is less violent and splash effects are smaller.

The Gunn-Bellani device is not affected either by wind speed or by the evaporation-sink factors of air-temperature and humidity. That under these limitations it should account for from 85 to 93 per cent of the variability in evaporation rates demonstrates the dominance of the radiation term, under East African high-altitude conditions, in the heat balance of open water evaporation.

The foregoing equations also show that, for the purpose of estimating evaporation, the simple distillation instrument is as effective as the thermopile solarimeter.

Where adequate instrumentation is possible, the factors of the Dalton equation should not be neglected, and evaporation rates have been computed by the Penman equation (Penman 1948) throughout the years 1948 to 1955. Agreement of the results with evaporation-tank data (Pereira 1955) was substantially improved by substitution of the distillation readings for the radiation term derived from sun-hours. Revision of this comparison, as a result of the subsequent improvement of the estimation of radiation from sun-hours by Glover and McCulloch (1958), is in progress.

7. Discussion

Used in the mounting described, the Gunn-Bellani instrument offers for East African conditions, a practical and convenient alternative to the troublesome open-water evaporation tank.

As irrigation schemes in the tropical semi-arid lands are carried further into conditions marginal for water supply, the economy and control of water applications become of vital importance. Quantitative continuous field measurements of evaporation rates are essential for such control. Measurement in absolute units is of secondary importance, since such evaporation data have usually to be modified by factors dependent on the crop. For practical field use in irrigation control the more robust glass-condenser model of the Gunn-Bellani radiometer is therefore most suitable. Ashcroft and Taylor (1953) used electrical resistance units calibrated to soil-moisture tension to assess irrigation requirements and compared the estimates derived from evaporation pans, solar-radiation measurements, and the combination of air temperatures and day length evolved by Blaney and Criddle (1950). In all cases crop factors, as developed by the latter, were used to modify the weather data. Water requirements computed from radiation measurements gave the highest correlation coefficients with the tension measurements (0·713), open-pan evaporation gave 0·693 and temperature-day-length 0·628. With coffee, a deeply rooted tropical crop, the advantages of further modifying evaporation data by a running soil-moisture storage estimate has been demonstrated by Pereira (1957).

In semi-arid areas radiation data are also in increasing demand for studies of solar-heating equipment. Facilities for the operation of delicate recording galvanometers are scarce, while the detailed supervision essential for operation of open-water evaporation tanks is difficult to ensure. In these circumstances the radiation integrator might well be used as an adequate field instrument.

In the more developed tropical areas there are many problems of crop research and irrigation practice where the low cost and simplicity of operation of the distillation instruments outweigh the loss in accuracy of radiation measurements, and the few available thermopile instruments could with advantage be used to provide local calibration facilities. Without expensive systems of automatic integration the extremely tedious evaluation of daily radiation totals from thermopile records is a severe limitation in the practical use of the more accurate equipment.

Acknowledgments

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Research on methods of forecasting storm surges on the east and south coasts of Great Britain

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SUMMARY

Recent work at the Tidal Institute has provided means of predicting storm surges at the River Tyne entrance, Immingham, King's Lynn, Lowestoft and Southend in the North Sea and Newhaven in the English Channel, from meteorological forecasts.

An investigation of surges at Aberdeen has not resulted in a completely satisfactory method of predicting external surges, which are generated outside the North Sea, so that their effects at ports further south have been allowed for by observing their magnitude at Aberdeen and applying an empirical rule which governs their amplification and rate of travel, after Corkan (1948). The disturbances generated inside the North Sea proper, at all the other North Sea ports except King's Lynn, have been correlated at intervals of 6 hr with quantities representing the tractive force of the gradient winds at chosen points in the sea, assuming a quadratic law of friction. The success of the formulae so produced is fully illustrated. For King's Lynn, tide and surge have been treated as an entity, and high- and low-water heights have been expressed as functions of the corresponding heights at the River Tyne and the local wind strength and direction.

The propagation of North Sea surges through the Straits of Dover has been studied using Newhaven observations, and it is shown that they travel from Lowestoft as free progressive waves, being attenuated by half. Depressions in the western approaches to the English Channel are also shown to be responsible for disturbances at Newhaven.

1. INTRODUCTION

As a result of the disastrous North Sea flood of 31 January and 1 February 1953, a research programme has been conducted under the Advisory Committee on Oceanographical and Meteorological Research of the Ministry of Agriculture, Fisheries and Food. The Liverpool Observatory and Tidal Institute was requested to provide methods of forecasting storm surges in the North Sea, English Channel, Bristol Channel and the Irish Sea. This paper attempts briefly to describe the results obtained for the North Sea and the English Channel.

To put the work into its correct perspective it is desirable to give a short account of the investigations into this subject which have previously been carried out at the Tidal Institute. Doodson (1924) made extensive correlations between daily mean values of sea level, wind and barometric pressure for Newlyn and Liverpool. The technique employed has been freely adapted by the present author. Amongst other conclusions, Doodson showed that disturbances could more often be generated by distant than by local winds. Doodson (1929) extended his investigations to the destructive storm surge of 6 and 7 January 1928, and first noted the tendency for an anti-clockwise progression of this and other disturbances around the North Sea.

It is most unfortunate that the comprehensive work by Corkan (1948) on surges at Dunbar and Southend is now virtually inaccessible, and a slightly fuller account is therefore given. His prime purpose was to establish a formula which would make the forecasting of surges at Southend a practical proposition. Having demonstrated from observational data, and beyond all reasonable doubt, the existence of external surges travelling southwards from Dunbar to Southend, he allowed for their effect at Southend by using Dunbar observations. This was unavoidable in the absence of any satisfactory method of forecasting this type of disturbance. The effect, at Southend, of winds inside the North Sea was represented by pressure-gradient data extracted from meteorological charts for specified points in the sea, assuming the tractive force of the wind to be proportional to the square of the wind velocity. Least squares solutions then provided estimates of the unknown coefficients in his empirical formula. In all this, Corkan found that he was justified in

neglecting the oscillatory approach to steady-state conditions in the wind effect, first indicated theoretically by Proudman and Doodson (1924), though the inertia of the water necessitated a time lag between wind and wind effect. The efficiency of his formula in hindcasting surges at Southend for the years 1928 to 1938 was amply demonstrated in many examples, and the paper concluded with a classification of surge types and a statistical study of surge frequencies at Southend. In a later paper Corkan (1950) examined the water movements accompanying a particular surge in the North Sea, a similar study of the 1953 surge being made by Rossiter (1954).

For a most comprehensive bibliography of international scope, reference should be made to that published by the Association d'Océanographie Physique in 1957.

2. Reduction of tidal data

It has now become common practice in this country to refer to water disturbances such as are under discussion in this paper as storm surges. This phrase has the advantage of indicating the intrinsically dynamic nature of the phenomenon. A storm surge may conveniently be described as the difference, due to meteorological causes, between the astronomical and observed tide, surface waves and slow periodic changes in mean sea level with periods of a week or more being ignored.

The elimination of the astronomical tide from tidal records at hourly intervals (for details, see Rossiter 1959) gives the data, henceforth called residuals.

3. External surges

The tidal station at Dunbar, as used by Corkan (1948), was closed in 1950, and data from Aberdeen have been used instead for representation of the external surge.

The residuals at Aberdeen, Dunbar, River Tees Entrance, Immingham and Southend were obtained for five occasions when meteorological conditions inside the North Sea were quiet. After correcting each for the local barometric effect, using the statical law, the Aberdeen residuals were correlated with those at each of the other ports in turn, using different time lags.

The correlation coefficients are plotted against time lags in Fig. 1. It has been assumed that (residual at $X)_t = m$ (residual at Aberdeen)$_{t-\tau}$ where m is a factor, and t and τ are measured in hr.

TABLE 1. External surges

	Surge		Tidal components							
			Lag of constituent on Aberdeen (hr)				Amplitude relative to that at Aberdeen			
	τ (hr)	m	M_2	S_2	K_1	O_1	M_2	S_2	K_1	O_1
Dunbar	1	1·20	1·1	1·1	1·2	0·9	1·23	1·19	1·08	1·09
River Tees	2	1·18	2·5	2·5	2·9	2·5	1·30	1·27	1·17	1·12
Immingham	4·5	1·35	4·7	4·9	4·9	4·9	1·71	1·61	1·33	1·28
Southend	10	1·15	11·3	11·6	10·7	10·1	1·53	1·28	1·00	0·98

Table 1 gives values of τ together with time differences and relative amplitudes of the major harmonic constituents. This table shows clearly that the progression of external surges down the East Coast possesses similar features to that of the tide to a high degree.

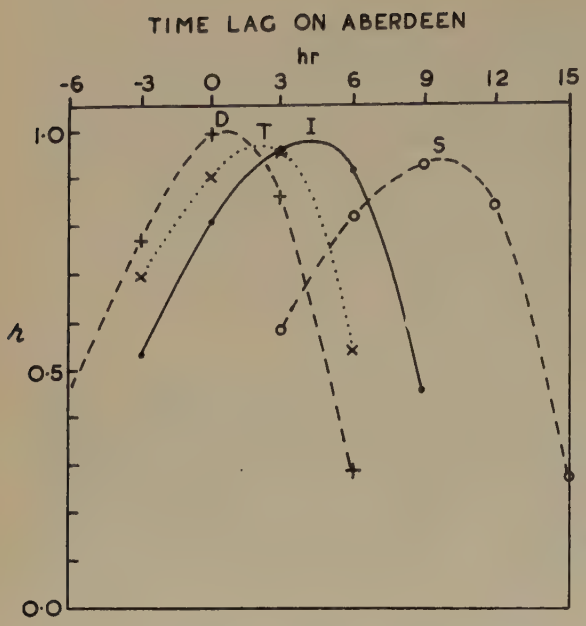


Figure 1. Correlation coefficients, for various time lags, between external surge residuals at Aberdeen and ports Dunbar (*D*), River Tees Entrance (*T*), Immingham (*I*) and Southend (*S*).

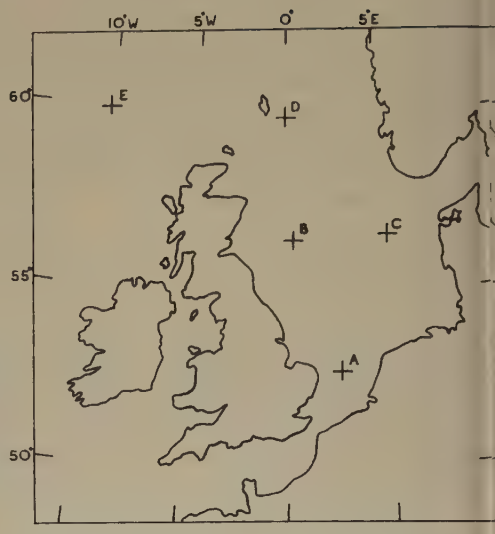


Figure 2. Points *A*, *B*, *C*, *D*, *E* at which pressure gradients were determined for North Sea surge research.

4. Meteorological data

In the absence of wind observations Corkan (1948), following earlier workers, determined quantities proportional to the geostrophic wind by using pressure gradients extracted from synoptic charts. Some criticism was levelled at his work on the grounds that the radius of curvature of the isobars was neglected. It was therefore decided in these investigations to use gradient winds rather than geostrophic winds.

Briefly, the procedure adopted was as follows. North (n) and east (e) pressure gradients were read off from the weather charts, each over a distance of 250 mi, for various points as required (see Fig. 2). The radius of curvature (r) was also estimated to the nearest 100 mi; this process is very subjective but the result is not critical to $\pm$ 200 mi. The main purpose of this refinement was to allow for the smaller wind velocities associated with isobars of high curvature, for a given pressure gradient, as opposed to those associated with straight isobars. By means of three double-entry tables for n, e and r quantities E and N were computed which are proportional to the easterly and northerly components of the tractive force of the gradient winds, assuming a quadratic law of friction. This is a simple and rapid process.

The researches show that the gradient wind does not give markedly better results than the geostrophic wind; see § 8 and also the statistical comparisons made by Reynolds (1956). He obtained for stations in the Irish Sea the following significant figures:

Correlation coefficient between geostrophic and surface wind velocities: 0·55.

Correlation coefficient between gradient and surface wind velocities: 0·52.

In the following, a symbol such as AE_{t-6} indicates the easterly tractive force component, positive from the east, at point A. 6 hr before a specified time t hr.

5. Preliminary correlations between surges at Aberdeen and Immingham, and the components of tractive force

Contingency tables were compiled for all notable surges between 1930 and 1938 inclusive, the variables being the components of tractive force of the wind and the corresponding surge so many hours earlier or later. Figs. 3 and 4 illustrate the results obtained. In all cases the ordinates are proportional to the covariance of residual and tractive force component. Time lags are in hr. The residuals are not corrected for barometric pressure changes. Figs. 3 and 4 display certain features which require comment :

(1) West winds cause a raising of level at both Aberdeen and Immingham, with time lags varying from 3 to 14 hr. For each of the points A, B and D the difference between the time lags at the two places is some 6 hr, comparable with the 5 hr indicated for external surges. A possible explanation of the generation of external surges is thus suggested, viz., westerly winds to the north and north-west of Scotland.

(2) Easterly winds were rare in the period considered, and the corresponding graphs are only given for the sake of completeness.

(3) North winds cause a raising of level, with a time lag somewhat less than 6 hr at both places.

(4) South winds give rise to a marked lowering of level at Immingham with a time lag of approximately 3 hr. The corresponding effect at Aberdeen is masked by the pressure effect, which is comparable in magnitude with the wind effect there. Nevertheless, this lowering is well established by a study of selected surges.

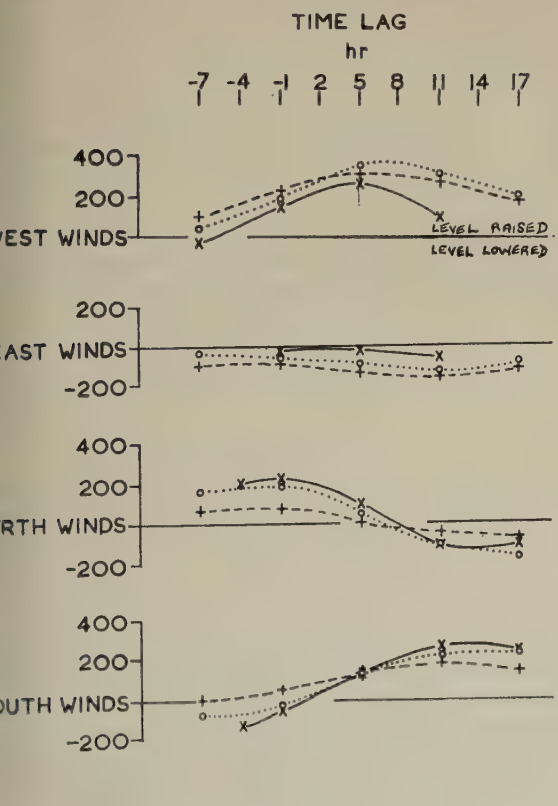


Figure 3.

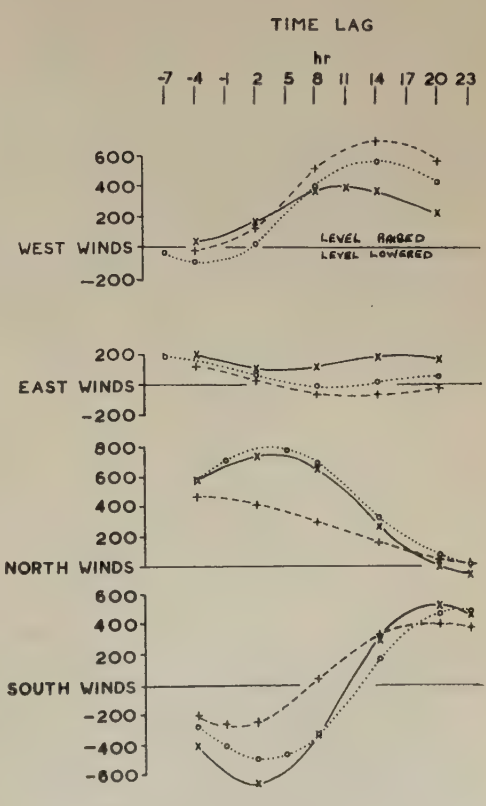


Figure 4.

Figures 3 and 4. Correlations, for various time lags, between observed residual and components of the tractive force of the wind, for Aberdeen and Immingham. Winds at A (– – + – –), B (· · · ○ · · ·) and D (—— × ——).

(5) Following a lowering of level produced by south winds, a pronounced rise in level occurs. At Immingham the peaks follow the troughs by approximately 18 hr, a figure which is in accord with estimates of 30 to 40 hr for oscillatory periods studied by Doodson and Corkan many years ago in unpublished work, and observed by other workers. A physical explanation of this is not hard to find; it is that south winds drive water out of the North Sea, the water ultimately returning southwards as a positive surge. Because both external and return surges are propagated down the East Coast as progressive waves under the influence of the earth's rotation, both types of disturbance may be represented in forecasting formulae by one expression, as will be shown in § 7. An example of a 'return' surge has been investigated in a separate work (Rossiter 1958).

6. Surges at Aberdeen

Similar conclusions for Aberdeen have been obtained from 20 surges in the period 1930 to 1938. The time lag between southerly wind and negative surge is approximately 3 hr. The succeeding positive surge has a time lag of about 15 hr.

A north wind over the approaches to the North Sea would be expected to generate a positive water gradient in a southerly direction. The subsequent decay of such a gradient would not be expected to cause any appreciable change at Aberdeen, other than a gradual return to mean level. The statistical work and the individual surges confirm this, and indicate a time lag of some 3 hr.

The remaining meteorological factor of importance is a west wind to the north-west of the sea, producing a rise in level at Aberdeen after some 5 hr have elapsed.

These conclusions suggest that the following empirical formula should give a fair representation of surges at Aberdeen :

$$\zeta_t = \underset{\text{(a)}}{\kappa\,(B_t - 1012)} + \underset{\text{(b)}}{\alpha\, DN_{t-3}} + \underset{\text{(c)}}{\beta\, BN_{t-15}} + \underset{\text{(d)}}{\gamma\, DN^{-}_{t-15}} + \underset{\text{(e)}}{\delta\, EE^{-}_{t-6}}$$

where terms such as DN_{t-3} have been defined in § 4. ζ_t is the surge height. $B_t - 1012$ is the deviation of the barometric pressure, at Aberdeen, from a mean of 1012 mb, and κ, α, β, γ and δ are constants.

The terms here allow for (a) the statical effect, assumed instantaneous; (b) the lowering or raising effect of S or N winds; (c) and (d) the return of water, represented by a south wind with a time lag of 15 hr; the (−) sign indicates that only negative values of N are to be used; (e) the effect of a west wind at point E with a time lag of 6 hr.

Assuming the theoretical value for κ, a least-squares solution of observations for 5 large surges gave

$$\alpha = 0{\cdot}037, \quad \beta = -0{\cdot}002, \quad \gamma = -0{\cdot}036, \quad \delta = -0{\cdot}024.$$

An improved formula was then sought, omitting BN and introducing BE, thus :

$$\zeta_t = \kappa\,(B_t - 1012) + \alpha'\, BE_{t-3} + \beta'\, DN_{t-3} + \gamma\, DN^{-}_{t-15} + \delta\, EE^{-}_{t-9} \quad . \qquad (1)$$

A least-squares solution was applied to 20 selected surges and gave

$$\alpha' = 0{\cdot}009, \quad \beta' = 0{\cdot}040, \quad \gamma = -0{\cdot}037, \quad \delta = -0{\cdot}034.$$

Computing the surges with these coefficients gave an absolute mean value for observed minus computed residual of − 0·10 ft, with a standard deviation of 0·67 ft, as compared with 0·62 ft and 1·00 ft respectively for the observed residual. These figures would seem to indicate that Eq. (1) could serve as no more than a rough guide to what might be expected at Aberdeen if used for forecasting purposes. Its failure probably lies in the fact that external and return surges are essentially dynamic phenomena, and cannot be adequately represented by formulae which assume that a state of equilibrium has been reached between wind and water.

It will be noted that consistency was obtained between α (0·037) and β' (0·040), for γ (− 0·036 and − 0·037) and for δ (− 0·024 and − 0·034).

7. Surges at Immingham

Had it been possible to obtain a formula for computing Aberdeen residuals from meteorological data to a high degree of accuracy, similar formulae for places further south would probably have been extensions of that for Aberdeen. The investigations of § 6 preclude this procedure, and it was therefore decided to adopt Corkan's type of formula (1948), viz :

$$\zeta_{x,t} = m\,\zeta_{A,t-\tau} + \alpha\,AE_{t-\tau_1} + \ldots + \alpha'\,AN_{t-\tau_1} + \ldots \quad . \quad . \quad (2)$$

where $\zeta_{x,t}$ = residual at X at time t and $\zeta_{A,t-\tau}$ = residual at Aberdeen at time $t - \tau$, both residuals being corrected for local barometric pressure effects. m and τ are defined in

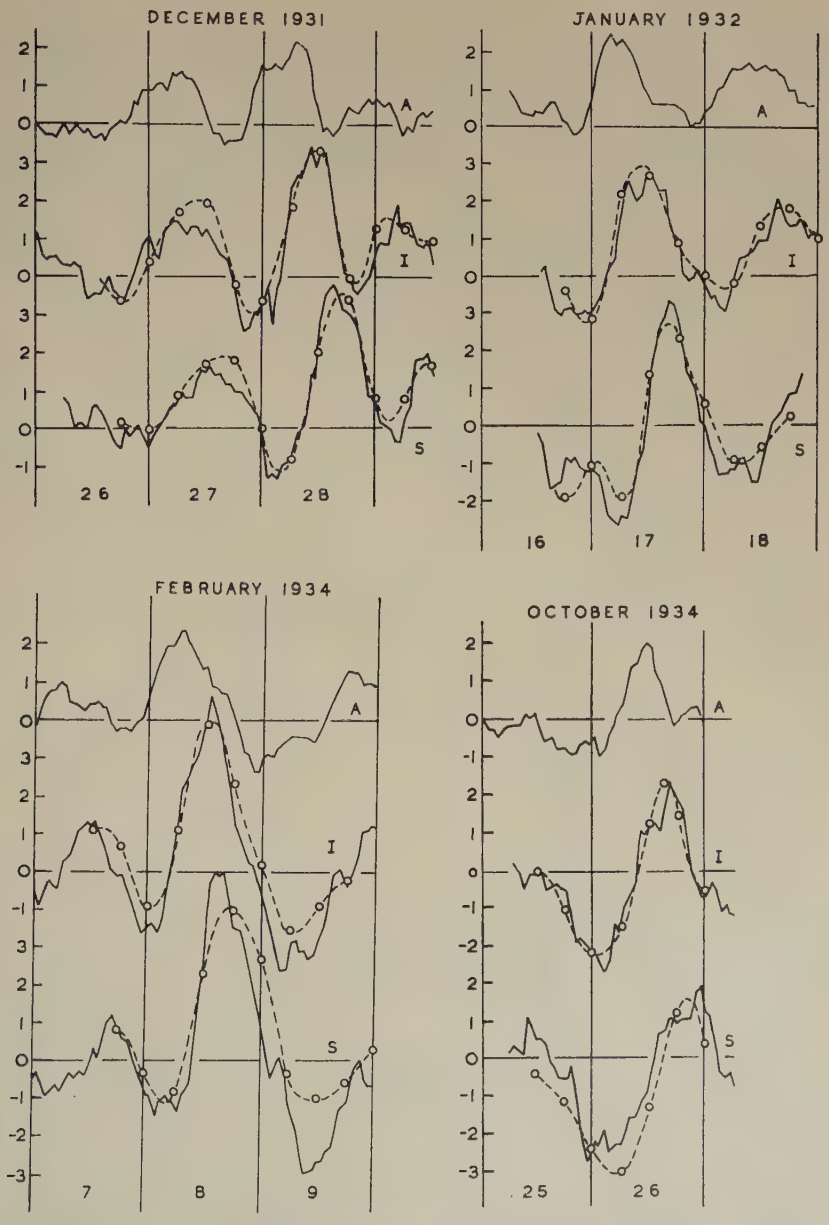


Figure 5 (a). Observed (———) and computed (– – ○ – –) residuals at Aberdeen (A), Immingham (I) and Southend (S). Height units are ft.

§ 3; $\alpha \ldots$, $\alpha' \ldots$, are constants to be determined, and $\tau_1 \ldots$ are time lags to be determined. The first term of Eq. (2) allows for the effect at X of both external and return surges, by utilizing observations at Aberdeen. The remaining terms express the wind effect produced inside the North Sea. To determine the best time lags for the wind effects when pressure gradients at more than one point are being used, a correlation system is generally better than a scrutiny of graphed residuals and wind components. Values of E and N extracted from the synoptic charts frequently show variations which tend to

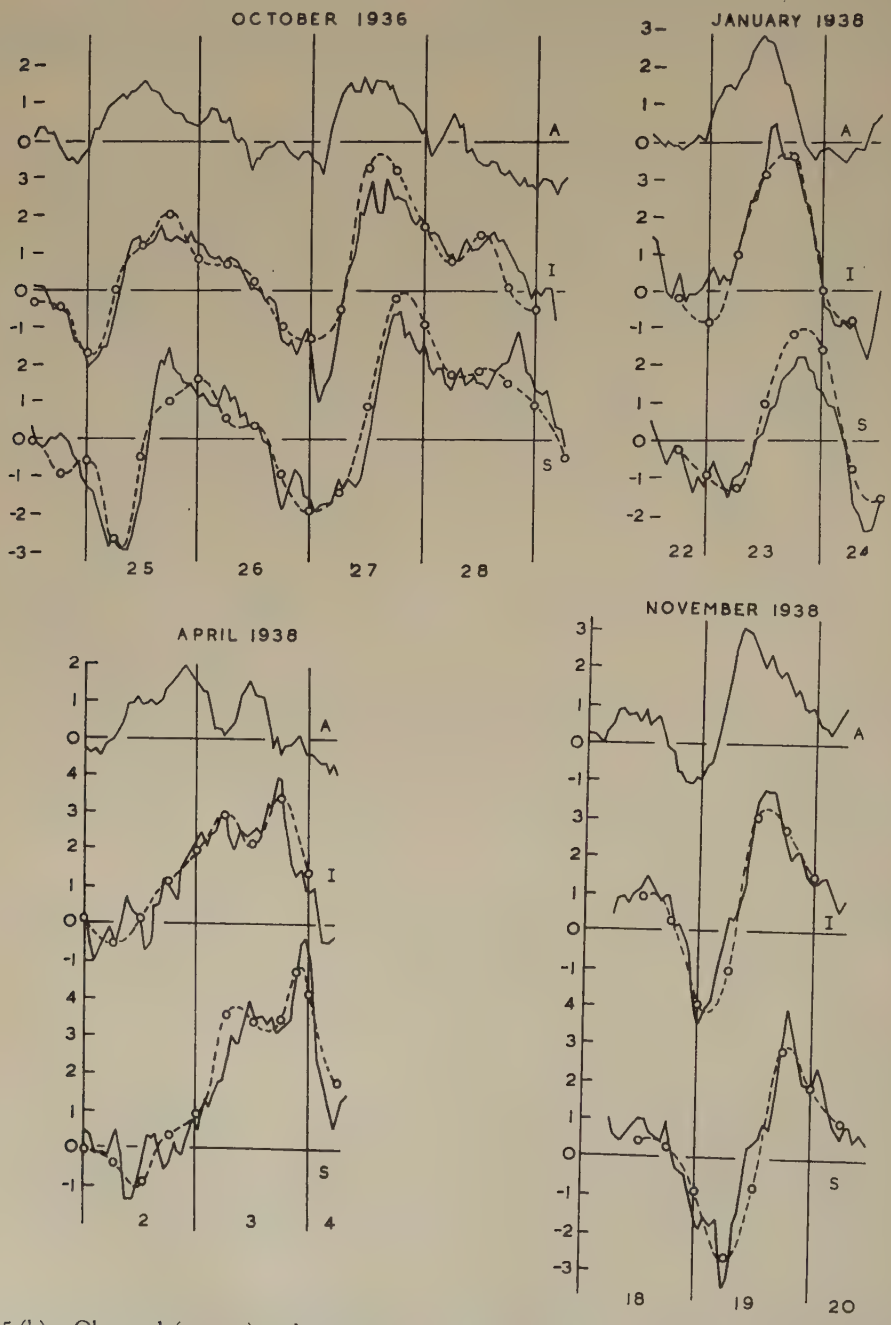


Figure 5 (b). Observed (———) and computed (– – ○ – –) residuals at Aberdeen (A), Immingham (I) and Southend (S) . Height units are ft.

cast doubt upon their accuracy. This was particularly noticeable for the 01 hr and 13 hr weather charts which did not cover the eastern half of the North Sea. It therefore became advisable to use points A and B for the meteorological data and omit point C.

Some 30 surges were selected from the period 1930 to 1938, and values of $\zeta_{I,t} - 1{\cdot}35\ \zeta_{A,t-5}$ at 6-hourly intervals were correlated in turn with the corresponding values of AE, AN, BE and BN. This involved approximately 250 values for each variable. In view of earlier indications that north winds would not necessarily have the same coefficients as south winds, positive and negative values of AN and BN were treated separately. Best fits were found with the equations

$$\zeta_{I,t} = 1{\cdot}35\ \zeta_{A,t-5} + 0{\cdot}021\ AE_{t-6} + 0{\cdot}004\ BE_{t-6} + 0{\cdot}059\ BN_{t-6} \quad . \quad . \quad (3a)$$

for northerly winds and

$$\zeta_{I,t} = 1{\cdot}35\ \zeta_{A,t-5} + 0{\cdot}021\ AE_{t-6} - 0{\cdot}008\ AN_{t-6} + 0{\cdot}004\ BE_{t-6} + 0{\cdot}036\ BN_{t-6} \quad (3b)$$

for southerly winds, which gave a total correlation of 0·93. Comparisons between some observed and computed surges using Eq. (3) are given in Fig. 5, and Fig. 6 illustrates the application to the 1953 surge.

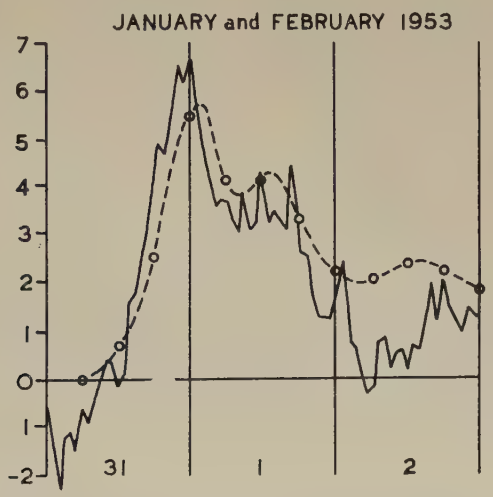


Figure 6. Observed (———) and computed (– – O – –) residuals at Immingham, 1953. Height units are ft.

8. Surges at Southend

A similar process was performed for Southend and a formula obtained, the quality of which is indicated in Fig. 5. Comparison between observed and computed surge was satisfactory and as for Corkan's formula (Corkan 1948) the 1953 computed surge was too high. The correlation formula therefore does not appear to mark any advance upon Corkan's formula.

It should be mentioned here that a series of tests were made, using least squares solutions, on five selected surges at Southend, one of them being the 1953 surge. The correction for the radius of curvature of the isobars was considered; various time lags for data for points A, B and C were employed. No combination appreciably improved upon Corkan's results, nor was there any combination which gave consistency between the coefficients for the 1953 surge and others. It may well be that the exceptional meteorological conditions obtaining in the 1953 surge violated the relationships between pressure gradients and the geostrophic and gradient winds.

9. Surges at the River Tyne entrance

Tidal records for the Tyne were then reduced for suitable occasions between 1930 and 1938, and 20 surges were selected in which winds over the North Sea were strong. These were submitted to a least squares solution of the formula

$$\zeta_{T,t} = 1{\cdot}2\,\zeta_{A,t-2} + \alpha\,BE_{t-\tau_1} + \beta\,BN_{t-\tau_1}$$

in the notation established

Solutions were obtained for $\tau_1 = 0$ and $\tau_1 = 6$ hr, and in addition the surges were sub-divided into those occurring with (a) northerly winds, (b) southerly winds and (c) southerly winds backing to northerly winds. The results are given in Table 2.

TABLE 2. Regression coefficients for River Tyne entrance

	α		β	
τ_1 (hr)	0	6	0	6
(a) N'ly winds	0·006	− 0·002	0·037	0·036
(b) S'ly winds	0·014	0·013	0·017	0·020
(c) S'ly winds backing N'ly	0·007	0·026	0·007	0·033

Taking all surges together we find

$$\alpha = 0{\cdot}005, \quad \beta = 0{\cdot}026 \quad \text{for} \quad \tau_1 = 0 \text{ hr}$$

$$\alpha = 0{\cdot}003, \quad \beta = 0{\cdot}030 \quad \text{for} \quad \tau_1 = 6 \text{ hr}.$$

There is a satisfactory degree of consistency, for each value of τ_1, between the mean and the individual results. There seemed to be little to choose between the two values of τ_1; a comparison of the standard deviations of the ultimate residuals, using the mean values of α and β, showed $\sigma = 0{\cdot}50$ ft for $\tau_1 = 0$ hr and $\sigma = 0{\cdot}44$ ft for $\tau_1 = 6$ hr. The following expression was therefore adopted for the Tyne :

$$\zeta_{T,t} = 1{\cdot}2\,\zeta_{A,t-2} + 0{\cdot}003\,BE_{t-3} + 0{\cdot}30\,BN_{t-3} \qquad (4)$$

It will be seen that time lag of 3 hr is suggested as a compromise, but in Fig. 7, which illustrates some observed and computed surges, a time lag of 6 hr was used for ease of calculation. The contributions to the residuals from the terms $\alpha\,BE$ and $\beta\,BN$ are in all cases small (usually less than 1·5 ft), and examination of the graphs will confirm that the Aberdeen residuals, moved on 3 hr and magnified by a factor of 1·2, closely represent the River Tyne residuals.

The compound correlation coefficient between the two sides of Eq. (4) is 0·92.

10. Surges at Lowestoft

Continuous tidal readings for Lowestoft have only become available since September 1953, and the figures given in this section are based solely upon surges occurring between this date and March 1956. The same technique of finding a least squares solution to the linear equation

$$\zeta_{L,t} = 1{\cdot}15\,\zeta_{A,t-8} + \alpha\,ABE_{t-\tau_1} + \beta\,ABN_{t-\tau_1}$$

was employed as in previous sections, where ABE, ABN represent the easterly and northerly components of the tractive force of the wind, averaged for points A and B.

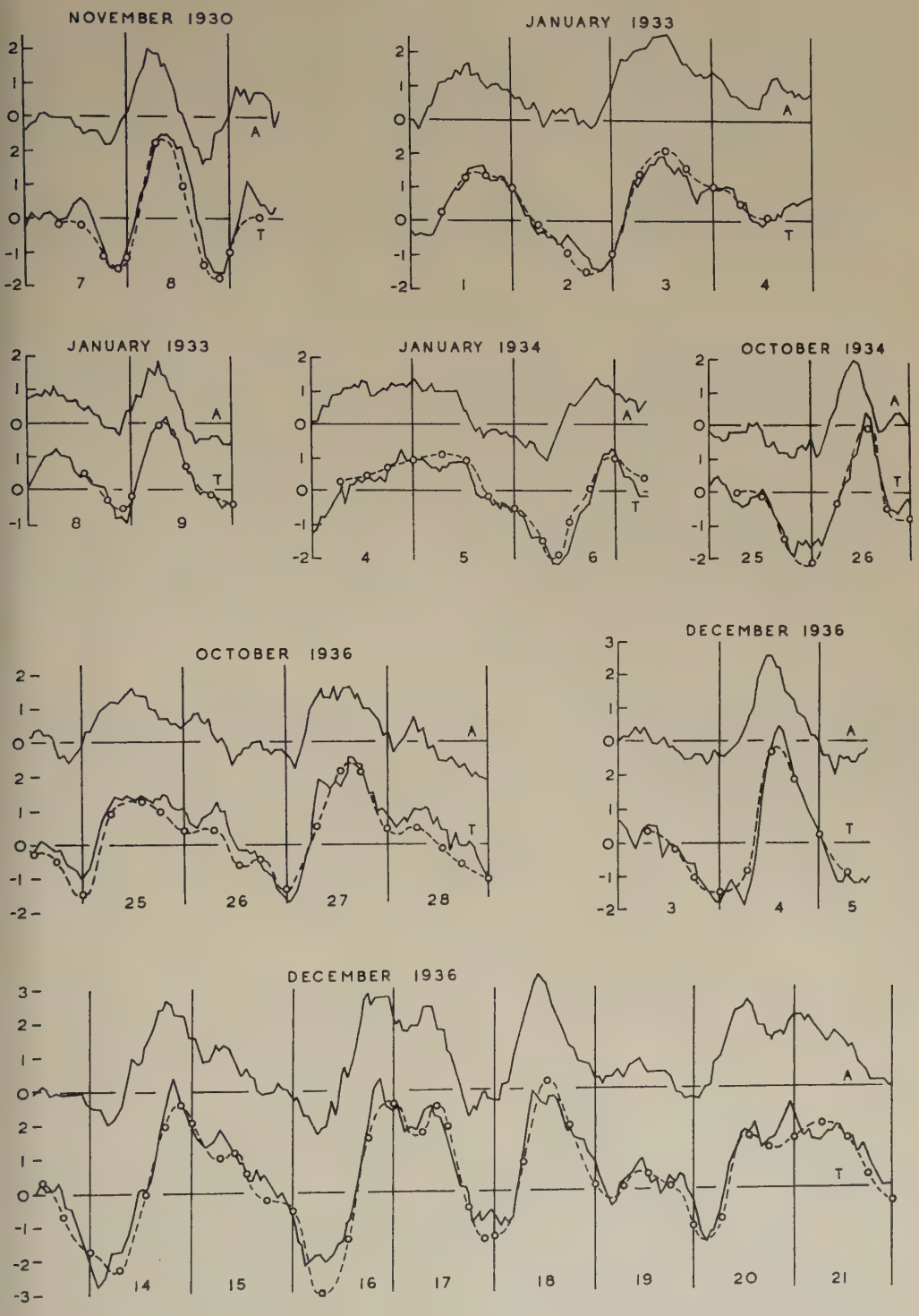


Figure 7. Observed (———) and computed (– – ○ – –) residuals at Aberdeen (A) and River Tyne (T). Height units are ft.

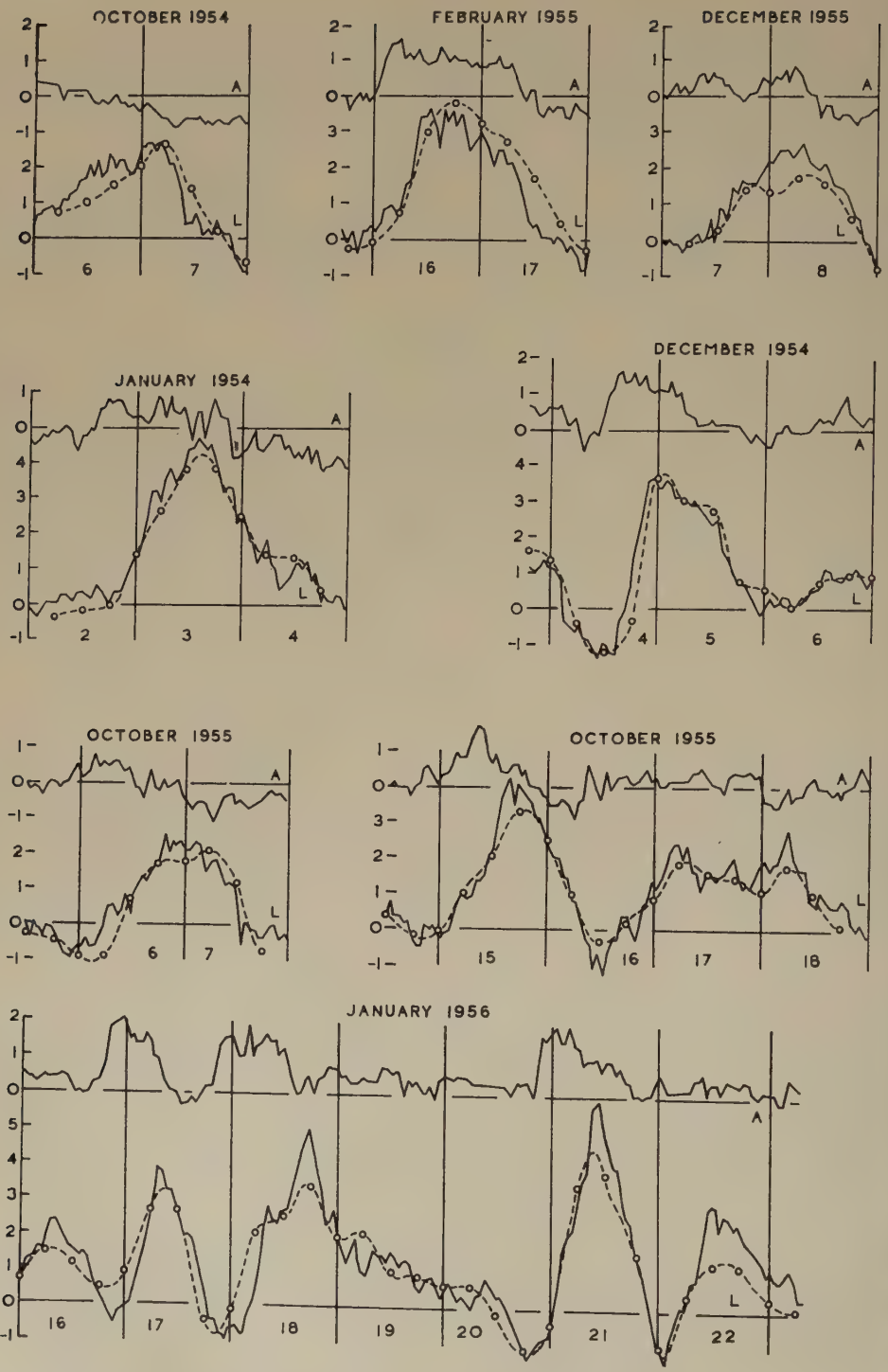


Figure 8. Observed (———) and computed (– – ○ – –) residuals at Aberdeen (A) and Lowestoft (L). Height units are ft.

From the indications of earlier work, and also from inspection of the basic data, a suitable value for the time lag τ_1, between wind and wind effect is 6 hr. Values of α and β were obtained from 7 cases in which winds were generally from a northerly direction throughout the disturbance (i.e. positive surges) and from 7 cases in which southerly winds veered to northerly (negative surges, usually small, followed by positive surges). Table 3 indicates the results obtained, and it will be seen that good agreement was obtained between (a) and (b).

TABLE 3. REGRESSION COEFFICIENTS FOR LOWESTOFT

	α	β	
(a) N'ly winds	− 0·016	0·140	7 surges
(b) S'ly winds veering to N'ly	− 0·028	0·123	7 surges

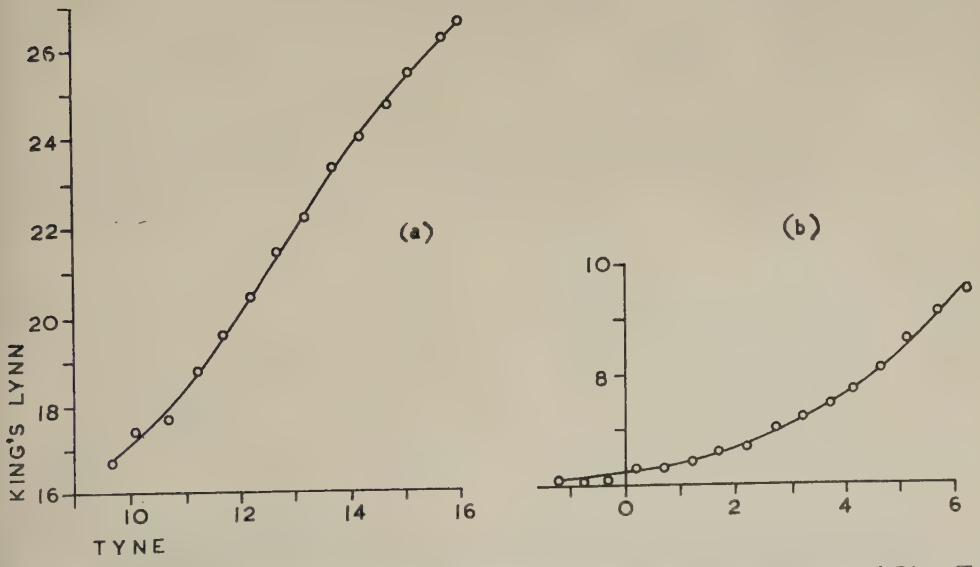
A direct average gave the formula

$$\zeta_{L,t} = 1{\cdot}15\ \zeta_{A,t-8} - 0{\cdot}025\ ABE_{t-6} + 0{\cdot}132\ ABN_{t-6} \quad . \quad . \quad (5)$$

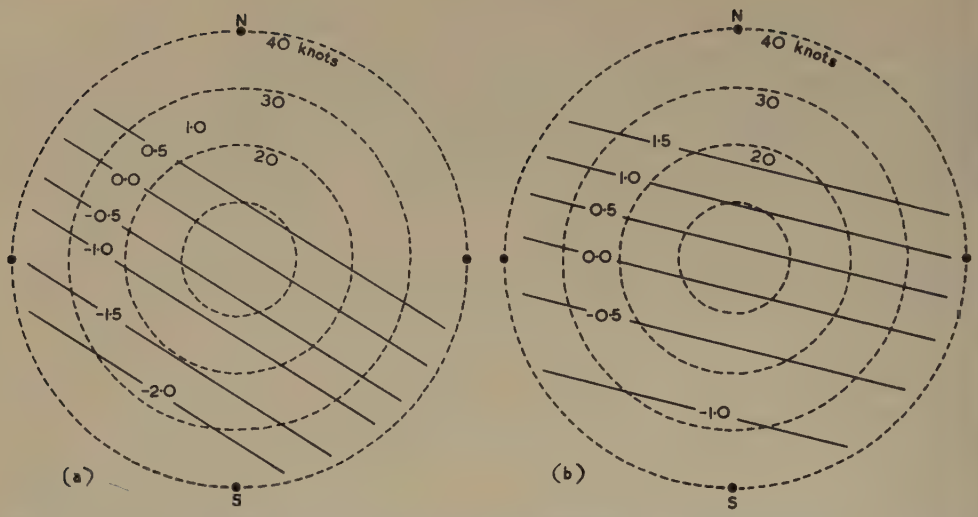
It is doubtful if Eq. (5) will give a good representation of large negative surges, or of surges in which strong southerly winds prevail. Comparisons of observed and calculated surges during the period are shown in Fig. 8

11. SURGES AT KING'S LYNN

In previous regional investigations of surges in the North Sea by Corkan (1950) and Rossiter (1954) it was obvious that local wind effects in the Wash were appreciable. A comparison between observations at King's Lynn and the River Tyne entrance was used to test this effect, firstly from high- and low-water heights for the meteorologically calm months of April to September 1955. The results are given in Fig. 9.



Figures 9 (a) and 9 (b). Relationship between observed heights of tide at King's Lynn and River Tyne entrance (a) high waters, (b) low waters. Height units are ft.



Figures 10 (a) and 10 (b). Observed minus expected heights of tide at King's Lynn for (a) high waters and (b) low waters, as functions of wind at Cranwell. Height units are ft.

The differences between the observed height of tide (O) at King's Lynn, and the corresponding expected value (*E*), as deduced from Fig. 9 using observations for the Tyne, were tabulated for all prominent surges during the period September 1953 to April 1956. These differences are entered in Fig. 10 as functions of the wind as recorded at Cranwell, after averaging at intervals of 5 kt in velocity and 30° in direction. Lines have been drawn at intervals of 0·5 ft joining, as nearly as possible, points of equal *O-E*.

It is clear that the directions and magnitudes of these lines agree with what could be expected from the orientation of the Wash, viz., that winds from the NE have the greatest level-raising effect at King's Lynn and SWly winds have the greatest level-lowering effect. In view of the time-keeping errors of the tide gauge, and the fact that surge and tide have here been treated as a single entity, the results must be considered satisfactory. Attempts to treat the times of high and low waters by the same method, though not so successful, revealed that when the local winds raise the level, the times of high and low waters tend to be advanced, this tendency being more marked at low water than at high. Conversely, winds from the SW quadrant delay the tide.

12. Surges at Newhaven

Newhaven was considered as being far enough removed from the Straits of Dover to exhibit any effects peculiar to the Channel, but not so far west as to enter the area where tidal shallow-water effects are so strong (e.g., Portsmouth, Southampton and Portland).

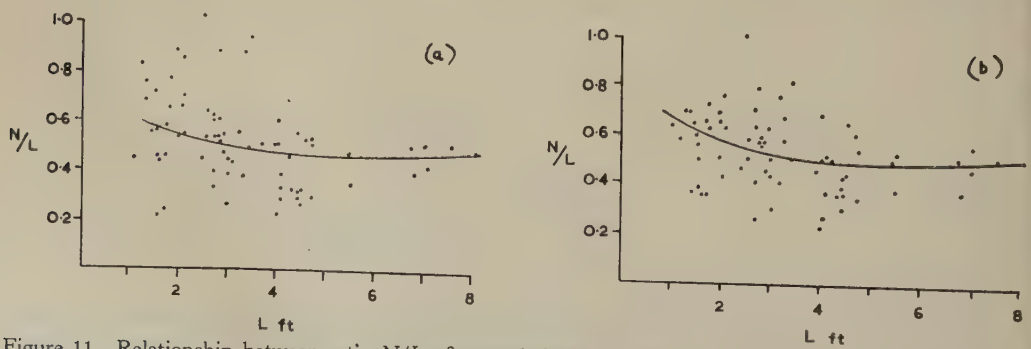


Figure 11. Relationship between ratio *N/L* of surge heights (*L* refers to Lowestoft and *N* to Newhaven) and the surge height at Lowestoft. Heights uncorrected (a) and corrected (b) for barometric pressure effect.

It was evident that the majority of disturbances occurring at Newhaven coincided with the existence of surges in the North Sea, and it was decided to obtain the residuals at Newhaven and compare them with the corresponding data for Lowestoft. Data available for the years 1953 to 1956 showed a mean time difference of 4·0 hr between the occurrence of surges at Lowestoft and Newhaven. Individual differences varied between 0 and 11 hr, with one exceptional case of 20 hr. This particular surge, that of 30 November 1954, will be discussed later.

Fig. 11 (a) illustrates the relationship between the ratio N/L of surge rise or fall (L refers to Lowestoft and N to Newhaven) and the surge height at Lowestoft. Fig. 11 (b) differs from Fig. 11 (a) only in that the Newhaven residuals were first corrected for the local barometric pressure effect. It will be seen that there is slightly less scatter in Fig. 11 (b) but both indicate a ratio of approximately 0·5, especially for large surges at Lowestoft.

On the basis of this evidence we may conclude that surges in the North Sea are propagated through the Straits of Dover in such a manner that they travel from Lowestoft to Newhaven in 4 hr and are reduced in amplitude by one half. This possibility had previously been indicated by Rossiter (1954), and further investigated by Bowden (1956). Confirmation of the speed of travel is forthcoming for, if we take the distance as 170 mi, the depth of water required for a free progressive wave to travel this distance in 4 hr is approximately 20 fathoms, a figure in excellent agreement with soundings on the appropriate Admiralty chart.

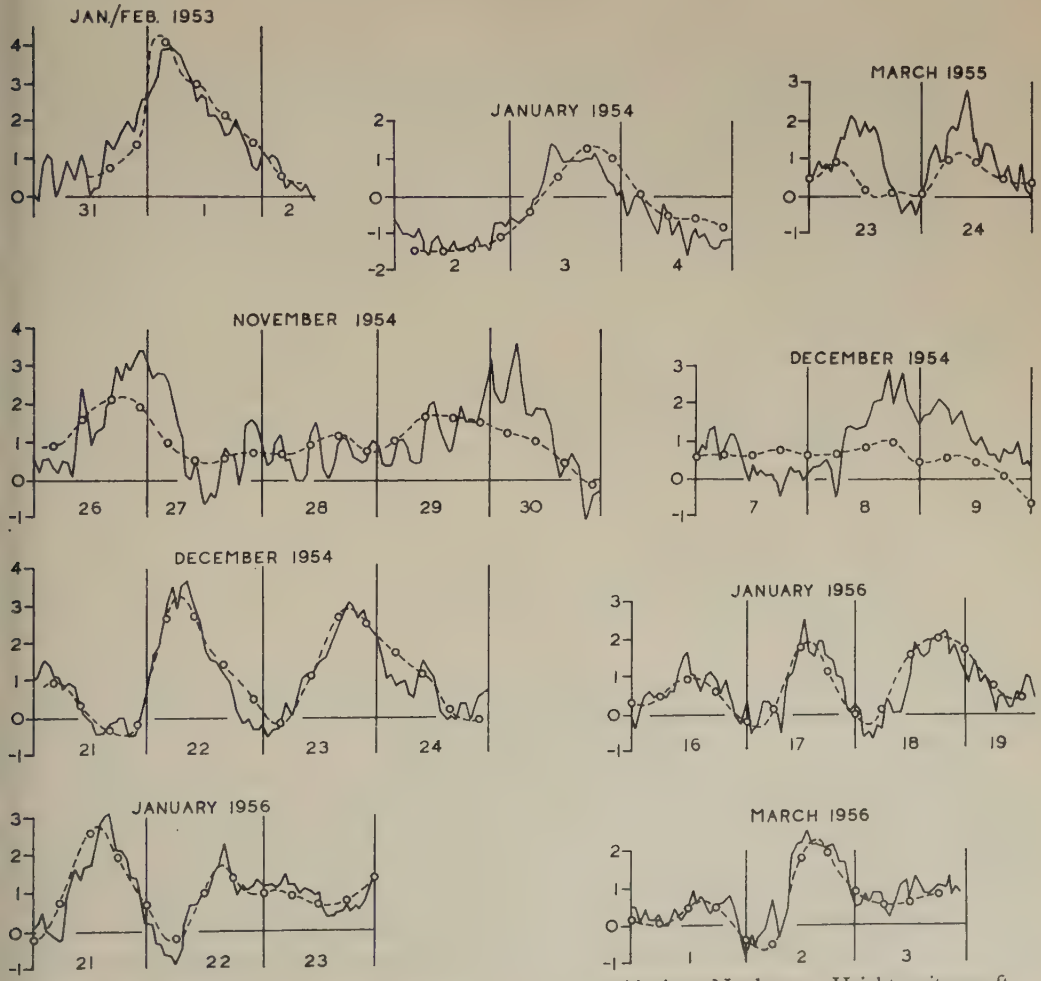


Figure 12. Observed (———) and computed (– – O – –) residuals at Newhaven. Height units are ft.

Examples of the application of this simple empirical law are given in Fig. 12, in which Newhaven residuals are plotted as continuous lines. It will be noticed that some tidal oscillations of a quarter-diurnal nature are present, but as they did not seriously interfere with the investigation it was not considered necessary to eliminate them. The pecked lines represent half the Lowestoft residual, 4 hr earlier, plus the difference between the barometric pressure effects at Newhaven and Lowestoft. In some cases it was found necessary to adjust the mean level of the pecked lines by an amount which is constant for long periods (at least 3 days). Such slow variations probably have their origin outside our marginal seas, and are of minor importance in this context. Examination of the data for occasions when the empirical law failed revealed 8 such cases. Half of these involved surges at Newhaven not exceeding 1·5 ft. For each of them there were similar oscillations at Lowestoft. The others are interesting in that two of them coincide with surges at Avonmouth studied by Lennon in his work on storm surges in the Bristol Channel, shortly to be published. This might have been anticipated in view of the similar geographical orientation of the Bristol and English Channels. He has shown that most of the largest surges in this area develop as a result of secondary depressions from the Atlantic following well-defined routes across the British Isles. The phenomenon referred to is essentially a dynamical one, the surge-generating force being the travelling wind field associated with the depression. The remaining two disturbances were accompanied by rather similar meteorological conditions, and these four exceptional cases are described in more detail :

(a) 27 to 30 November 1954.

A surge at Lowestoft on 26 November was transmitted through to Newhaven as indicated by the pecked line, but the residuals were then considerably modified by the secondary depression that produced a surge of 5·5 ft at Avonmouth at 04 hr on 27 November. A surge at Lowestoft on 29 November was likewise propagated down to Newhaven and modified by the secondary depression that produced a surge of 8·2 ft at Avonmouth at 05 hr on 30 November. In both cases there is a close correlation between the pressure gradient in the section Land's End to Finistère and the difference between the observed residual and the pecked line.

(b) 6 to 9 December 1954.

During this period there was a tendency for a secondary depression to develop in the western approaches to the Irish Sea and the English Channel, but the pressure gradient Lennon has shown necessary to produce an appreciable surge at Avonmouth did not develop.

(c) 23 and 24 March 1955.

The disturbances on these two days are closely related to the very good examples of secondary depressions existing at the time.

To complete the investigation, all dates on which strong winds were recorded in the Channel were noted, and compared with those dates for which residuals had been extracted. In no case was it apparent that such winds could generate surges at Newhaven of magnitude comparable with those transmitted through the Straits of Dover. It would therefore appear that any disturbance generated by westerly winds over the Channel area must be very largely concentrated on to the French coast by the earth's rotation, substantially transmitted through the Straits of Dover to continue northwards along the European North Sea coast. Indeed, research workers in the Netherlands, e.g. Schalkwijk (1947), have found it necessary to include an ' English Channel ' effect in their forecasting formulae for the Dutch coast. The above results would also suggest that Holland may to some extent be affected by the same secondary depressions that are so important on our West Coast.

Acknowledgments

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Exchange of heat, moisture and momentum between *Hurricane Ella* (*1958*) and its environment

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(Manuscript received 12 January 1959)

Summary

On 2 September 1958, a tropical storm moved near the centre of the network of upper-air observations in the Atlantic and Caribbean SE of Florida. This made possible determination of the structure of the storm at a radius of 4·5° latitude from the centre through the entire troposphere and computation of surface integrals concerning the exchange of heat moisture and momentum between the storm and its surroundings. It was found that a net heat export occurred, indicating a net tropospheric drying and cooling after inclusion of the effect of radiation. The inward transport of relative angular momentum was insufficient to balance the flux of angular momentum to the ground as estimated from calculations for the mean hurricane. These computations then suggest weakening of the disturbance with time, and this actually occurred.

1. Introduction

From the mean distribution of temperature, wind and moisture in hurricanes, Palmén and Riehl (1957) have made estimates of heat and energy budget in these cyclones; they have also considered the balance of absolute angular momentum. Owing to lack of a sufficiently dense network of radiosonde and rawin observation stations around tropical storms it has never been possible, so far, to compute heat and momentum exchange between hurricanes and their surroundings on a synoptic basis. In this respect, a new opportunity for computations arose when, on 2 September 1958, *Hurricane Ella* moved near the centre of the network of upper-air stations southeast of Florida.

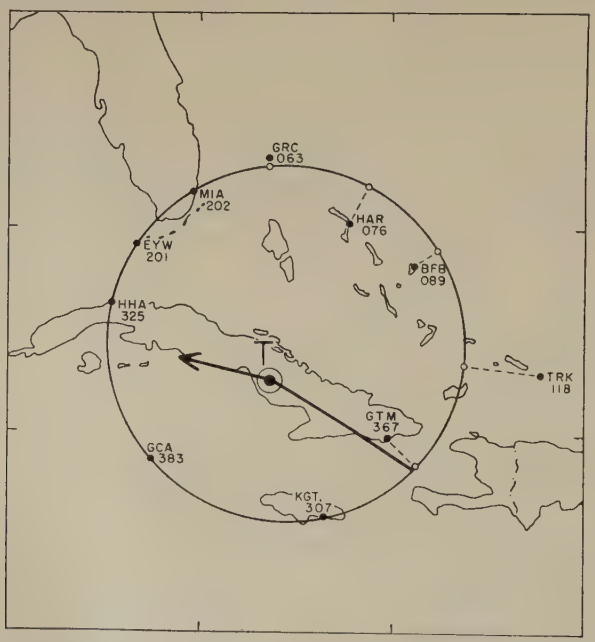

Figure 1. Network of upper-air stations in the Bahamas circle.

* Performed this work while assigned to the University of Chicago and the United States Weather Bureau.

† Participated under contracts between the Office of Naval Research and the United States Weather Bureau with the University of Chicago.

Fig. 1 shows the position of these stations and the path of *Ella*. The latter had attained hurricane strength while in the eastern Caribbean, but the eye was lost after crossing the mountains of eastern Cuba. This weakening occurred in the 12 hr preceding the time when the storm moved close to the middle of the station network of Fig. 1, which will be referred to as the Bahamas circle. The following calculations will be representative for the hurricane at this stage of diminished intensity, although it is probable that on the Bahamas circle – 4·5° latitude distant from the cyclone centre – most of the features of the circulation were still indicative of hurricane structure.

2. Structure of the circulation

The basic quantities analysed were the tangential wind component (v_θ, positive cyclonic), the radial wind component (v_r, positive outward), the specific humidity (q) and the enthalpy plus potential energy, denoted by $gz + c_p T$ where g is acceleration of gravity, z height, c_p specific heat at constant pressure and T temperature. For each of the 10 soundings on the Bahamas circle these quantities were plotted on diagrams with pressure as ordinate on a linear scale. After drawing curves, mean values were obtained for layers of 100-mb thickness from 1,000 to 200 mb and for layers of 50 mb thickness from 200 to 100 mb. Vertical cross-sections were then prepared for each of the four variables of which those for the wind components and moisture are shown in Figs. 2-4. As generally found in the tropics, variations of gz and $c_p T$ were small, and this cross-section has, therefore, not been included.

The tangential component (Fig. 2) exhibited considerable fluctuations around the circle. An axially symmetric circulation did not exist, even though the mean tangential component averaged around the circle ($\bar{v}_\theta$) may be presumed to be in quasi-gradient equilibrium. It is apparent, however, that the circulation was predominantly cyclonic in low and middle troposphere, with strongest v_θ to the right of the direction of centre propagation, in agreement with the asymmetry normally observed in moving cyclones. In the high troposphere, the flow became increasingly clockwise, with strongest anticyclonic motion in the sector from NW to NE of *Ella*.

Prior to preparation of the cross-section for the radial component (v_r), the storm displacement (c) was subtracted vectorially from v_r to yield the radial component relative to the moving centre (v_{rr}). Through this step one obtains the speed with which air actually approached or moved away from the centre. Variations of v_{rr} around the circle (Fig. 3)

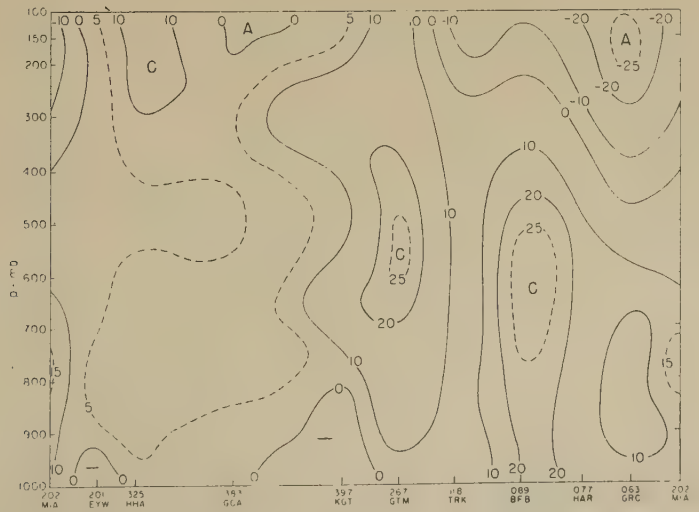

Figure 2. Vertical cross-section of the tangential component of motion (kt), 2 September 1958, 12 GMT.

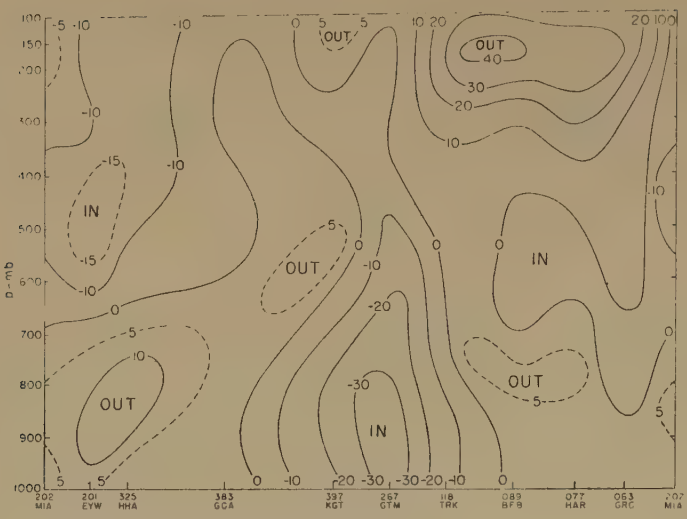

Figure 3. Vertical cross-section of the radial component of motion (kt), after vectorial subtraction of the storm displacement, 2 September 1958, 12 GMT.

were even larger than those of v_θ, and this must be expected. While the individual wind vector is largely in gradient balance, the net radial component around a closed curve, in contrast to the net tangential component, must represent purely ageostrophic motion across the isobars. From Fig. 3 it is evident that all low-tropospheric inflow took place to the rear of the storm, while ahead of it there was a broad region of outbound motion even in the coordinate system moving with the centre. Such an arrangement of v_{rr} is normally observed in hurricanes moving at a moderate speed in the tropics; a general overtaking of the cyclone by the low-level flow is indicated. Most outflow occurred NW of *Ella*, fairly well correlated with the area of anticyclonic flow in Fig. 2.

Considering, next, moisture, the mean vertical distribution of specific humidity was at first ascertained by averaging the 10 soundings in each layer of 100-mb thickness. The mean moisture sounding was then subtracted from the individual soundings to yield the deviations from the mean at constant pressure; these deviations were plotted on the

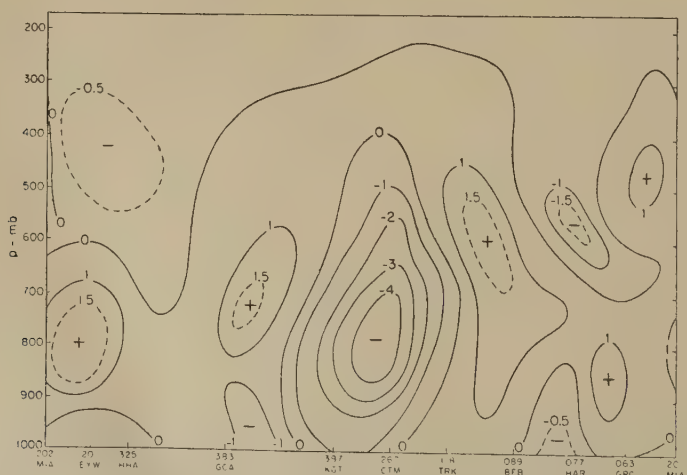

Figure 4. Vertical cross-section of the deviations of specific humidity (g kg^{-1}) from the mean vertical distribution for the Bahamas circle stations, 2 September 1958, 12 GMT.

cross-section and analysed (Fig. 4). This procedure is necessary if lateral moisture gradients are to be shown clearly. Normally the vertical specific humidity gradient is much larger than the horizontal gradient, so that sections prepared without removal of the mean indicate little except general upward decrease of humidity. In Fig. 4, as is reasonable, lateral moisture variations were largest at some distance above the ground where vertical motions are strong. They decreased both toward the ocean surface where the vertical motion vanishes and also toward the high tropospheric where the saturation specific humidity becomes small. Outstanding is the fact that negative anomalies of specific humidity prevailed where air was flowing toward and positive anomalies where air was flowing away from the centre. This reveals the action of the hurricane in building up a deep moist layer in the interior through convergence of the inflow, which is what produces the observed anomaly pattern around the boundary.

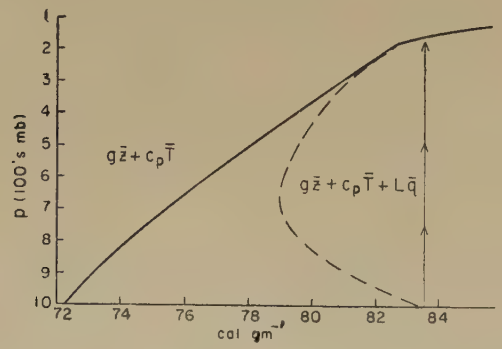

Figure 5. Vertical profiles of $g\bar{z} + c_p\bar{T}$, and of $g\bar{z} + c_p\bar{T} + L\bar{q}$ (cal gm^{-1}) averaged around the Bahamas circle, 2 September 1958, 12 GMT.

The mean vertical distribution of $gz + c_p T$ around the circle (Fig. 5) did not deviate notably from that normally found in the area under discussion during summer. After inclusion of the latent heat content Lq (L = latent heat of condensation) the dashed curve is obtained with a mid-tropospheric minimum which is typical of practically all tropical soundings (Riehl and Malkus 1958). Near the surface $Q_0 = (c_p T + Lq)_0 \approx 83$ cal gm^{-1}, a value which was nearly constant around the circle. Except for additions to Q_0 in the interior of the circle due to heat transfer from the ocean – probably small in this instance because the hurricane-force winds had disappeared – moist adiabatic ascent at 83 cal gm^{-1}, represented by the vertical line with arrows in Fig. 5, is the warmest possible ascent. The tropospheric circulation cell must end at about the pressure where this ascent intersects the mean sounding because the height of the tropopause and the high tropospheric temperature structure remain virtually unchanged from day to day. This intersection occurred near 150 mb, and for this reason all the following calculations will be confined to the troposphere below 150 mb. As evident from Figs. 2-3, tangential and radial circulations did not terminate there, which points to existence of a stratospheric cell higher up.

The mean tangential circulation (Fig. 6) was cyclonic through most of the troposphere, with net clockwise flow only above 200 mb. In this respect, the profile was more typical of large hurricanes than of smaller tropical storms where upper anticyclonic flow has been observed to extend through much deeper layers with speeds approximating those of the lower cyclonic flow. The fact that the circulation was strongest in the layer 700-600 mb is not necessarily related to weakening of the hurricane core. Studies of individual rawin ascents around hurricanes have produced the impression that such a structure occurs frequently in the outskirts even of large hurricanes and typhoons.

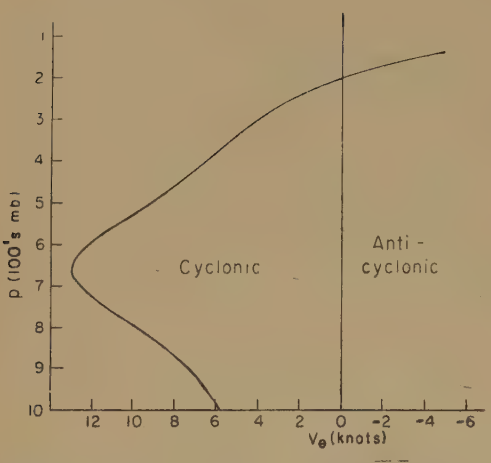

Figure 6. Vertical profile of the tangential wind component (kt) averaged around the Bahamas circle, 2 September 1958, 12 GMT.

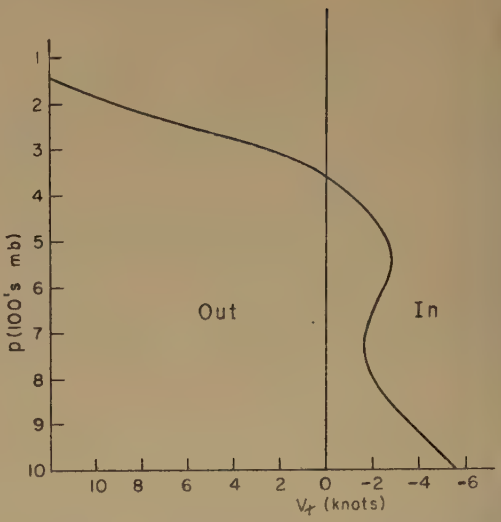

Figure 7. Vertical profile of the radial wind component (kt) averaged around the Bahamas circle, 2 September 1958, 12 GMT.

The profile of the mean radial component $\bar{v}_r$ (or $\bar{v}_{rr}$), adjusted slightly so that mass inflow and outflow balance, is surprising in two respects (Fig. 7). One of these is the depth of the inflow layer, the other, the strength of the non-geostrophic wind especially in the high troposphere, where this component attained the magnitude of the total wind. Usually, the net ageostrophic component is a small residual of alternating indrafts and outdrafts which are individually quasigradient. Such alternation was indeed noted in Fig. 3. Nevertheless, the residual was large, and hence may be considered as more reliable than is usual in such calculations. Similar calculations were performed at 12-hr intervals while the hurricane was inside the circle. Three successive 12-hr periods yielded profiles almost identical to that of Fig. 7, with regular transition as *Ella* entered and left the Bahamas circle.

The high level of non-divergence was not expected in earlier studies (cf. Riehl 1954), but recent computations for Gulf of Mexico cyclones (Riehl 1959) have revealed similar mass circulation profiles. Because of the mid-tropospheric minimum of $gz + c_p T + L_q$ in Fig. 5, it was held previously that only low-tropospheric air with high heat content can penetrate into the interior of hurricanes if such storms are to be warmer than their surroundings. Recently, Simpson and Riehl (1958) found from research aircraft flights that mid-tropospheric 'ventilation' takes place even in the core of well-developed hurricanes, i.e., a wind component v_{rr} exists in the layer of minimum Q which brings some air laterally into the core which is not derived by ascent from the surface layer. Nevertheless, the mean component $\bar{v}_r$, averaged around circles from flight data near 600 mb, was small on these occasions compared to $\bar{v}_r$ in the surface layer indicating that the earlier hypothesis on mass circulation is still largely valid.

It may be concluded that the bulk of mass entering the circle above 800 mb in Fig. 7 did not penetrate into the central parts of the cyclone but that it ascended in the outskirts. This hypothesis is supported by research aircraft observations from three airplanes made into *Ella* by the National Hurricane Research Project shortly after the sounding period here analysed. The observers (including one of the authors) found that the principal heavy rainbands were located far to the east of the centre near longitude 77°-76°W. Quantitative evaluation of the mass circulation from the aircraft traverses in low and middle troposphere cannot be made because the planes stayed on the eastern side of the centre. At 235 mb, however, the B-47 jet airplane executed an irregularly shaped pentagon around the storm with mean radius of about 2° latitude. The net mass transport through this pentagon was almost zero, very different from Fig. 7.

From these and other data on the wind structure of hurricanes and near-hurricanes one obtains the impression that an intense and deep mass circulation commonly exists at a considerable distance from a centre, and that only a small fraction of this mass penetrates to the core.

3. Heat and moisture budget

On 2 September, 12 GMT, *Ella* was located quite close to the geometric centre of the Bahamas circle which is slightly off the northern coast of Cuba. This position, plus the circular arrangement of the stations, suggests a cylindrical coordinate system (r, θ, z) for computing the interaction between the storm and its environment. Utilizing the relative framework discussed earlier, the export and import of heat, moisture and momentum with respect to the travelling centre can be obtained. In the relative coordinate system the heat transport through the cylinder is given by :

$$H = \int\int (gz + c_p T)\, v_{rr}\, r d\theta \frac{dp}{g}, \quad . \quad . \quad . \quad . \quad (1)$$

and the moisture (latent heat) transport by :

$$M = \int\int Lq\, v_{rr}\, r d\theta \frac{dp}{g}, \quad . \quad . \quad . \quad . \quad (2)$$

where p is pressure and a top has been assumed for the tropospheric circulation cell as already discussed. Much interest centres on the question whether fluxes are produced primarily by the ageostrophic mass circulation or by lateral asymmetries around the cyclone as apparent from Figs. 1-3. Denoting means at constant pressure around the cylinder with bars and deviations with primes, the moisture transport becomes :

$$M = \overline{M} + M' = \int\int L\bar{q}\, \bar{v}_r\, r d\theta \frac{dp}{g} + \int\int L\overline{q' v'_{rr}}\, r d\theta \frac{dp}{g} \quad . \quad . \quad . \quad (3)$$

Similarly, the heat transport :

$$H = \overline{H} + H' = \int\int (c_p \bar{T} + g\bar{z})\, \bar{v}_r\, r d\theta \frac{dp}{g} + \int\int \overline{(c_p T' + gz')\, v'_{rr}}\, r d\theta \frac{dp}{g} \quad . \quad (4)$$

Values of the deviations q' and v'_{rr} were determined for each layer of 100-mb thickness (50 mb for the top layer) from a grid of 15 points spaced evenly around the cylinder. Through numerical integration of Eqs. 3 and 4 the following results were obtained (units 10^{14} cal sec^{-1}).

TABLE 1. Flux of moisture and heat by mean and eddy transport

$\overline{M} = -1{\cdot}4$	$\overline{H} = 1{\cdot}4$	
$M' = \ 0{\cdot}2$	$H' = 0{\cdot}1$	$M + H = 0{\cdot}3$
$M = -1{\cdot}2$	$H = 1{\cdot}5$	

Evidently the 'eddy' transports are very small compared to the transports by the mass circulation. However, since $\overline{M} + \overline{H} = 0$, the net export of heat arises from the lateral asymmetries alone. One may question whether the net export can be accepted as reliable since neither heat nor moisture-flow computations can be expected to be accurate to better than 10 per cent, if that much. It may be noted, however, that the net radiation cooling of the vortex was $0{\cdot}2 \times 10^{14}$ cal sec^{-1}, assuming a mean cooling rate of 1·0°C day^{-1}. Thus the calculated export has the magnitude of the cold source.

Another route may be employed to obtain a check on the validity of the moisture budget. If the time rate-of-change of total moisture in the vortex and the evaporation are small, the inward transport of moisture must equal the precipitation from continuity. Ordinarily no rainfall data exist over the oceans, so that the precipitation must be left as residual in moisture-balance calculations. The area enclosed by the Bahamas circle, however, contains many islands reporting 6-hourly precipitation. Maps of 24-hr precipitation can be prepared and integrated by means of an equal-area grid after drawing isohyets. Such charts were made daily for August and September 1958. Of course, the margin of error in the analyses can be large, but in general the station density proved sufficient to give a good indication of the rainfall pattern.

The integrated precipitation depth for the interval 2 September, 00 GMT to 3 September, 00 GMT, which is centred on the period of the computations, was 0·95 in., compared to a computed rainfall of 1·08 in. from $M = -1{\cdot}2 \times 10^{14}$ cal sec^{-1}. This is good agreement, especially when it is considered that an isohyetal map nearly always underestimates the actual precipitation. For comparison, integrated precipitation amounts were :

0·20 in. for 12 GMT, 1 September, to 12 GMT, 2 September
0·97 in. for 12 GMT, 2 September, to 12 GMT, 3 September
1·08 in. for 12 GMT, 3 September, to 12 GMT, 4 September
0·14 in. for 12 GMT, 4 September, to 12 GMT, 5 September

after the cyclone had left the Bahamas circle. It is seen that increase and decrease of average precipitation over the area took a very regular course as the storm first entered and later departed from the area. The good result may be ascribed to the fact that a large cyclonic wind system with an extensive precipitation shield was involved, rather than just local convection cells.

4. Angular momentum transport

Complete equations for the time rate-of-change of relative angular momentum with respect to the cyclone centre ($v_\theta\, r$) in a cylindrical coordinate system fixed in a moving storm have been worked out by Mihaljan (to be published). These show that the transport of absolute angular momentum through the cylinder is given by the transport of relative angular momentum measured with respect to the moving coordinate system, i.e. :

$$\frac{\delta \Omega}{\delta t} = -\int\int (r\, v_{\theta r})\, v_{rr}\, r d\theta \frac{dp}{g} \text{ plus other terms} \quad . \quad . \quad . \quad . \quad (5)$$

depending on integration within the volume bounded by the cylinder. Here $\delta/\delta t$ denotes time differentiation following the moving storm and Ω the relative angular momentum integrated over the mass inside the cylinder. A complete momentum budget cannot be computed since this would require knowledge of the three-dimensional wind and mass field. Therefore, in all of the following, only the effects of interaction between the vortex and its environment through the boundary cylinder can be discussed. We may note that $v_{\theta r} = v_\theta - c \sin\theta$, if θ is counted counter-clockwise beginning with the direction from which the storm moves. Entering this definition in Eq. 5 and introducing mean values and deviations around the cylinder,

$$\begin{aligned}\frac{\delta \Omega}{\delta t} &= -\,\overline{T}_\Omega - T'_\Omega + T_c \\ &= -\int\int r\, \overline{v}_\theta\, \overline{v}_r\, r d\theta \frac{dp}{g} - \int\int \overline{r\, v'_\theta\, v'_{rr}}\, r d\theta \frac{dp}{g} + \int\int r\, c\, \overline{\sin\theta\, v'_{rr}}\, r d\theta \frac{dp}{g} \quad . \quad (6)\end{aligned}$$

noting that $\overline{v}_{rr} = \overline{v}_r$. Evaluation of Eq. 6 yields the following results (units 10^{23} g cm^2 sec^{-2}).

TABLE 2. FLUX OF MOMENTUM BY MEAN AND EDDY CIRCULATIONS

$-T_{\Omega} = 5{\cdot}4$	
$-T_{\Omega}' = 0{\cdot}01$	$-T_{\Omega} + T_c = 6{\cdot}4$
$T_c = 1{\cdot}0$	

There was net inward transport of relative angular momentum due to T_{Ω} and T_c, while the contribution from T_{Ω}' was negligible. The term T_c is interesting in that it states explicitly the connexion between the rate of centre propagation and $\delta\Omega/\delta t$. T_c of course vanishes for stationary cyclones. For a moving disturbance, T_c will have a retarding effect on growth and maintenance of the system when net inflow occurs to the right and net outflow to the left of the direction of motion looking downstream, assuming $\sin\theta$ is measured as stated above. In our case, low-level inflow and outflow had maxima just on the direction of motion (Fig. 2), hence the low troposphere contributed little to T_c. The outflow occurred to the right of the direction of motion, and this position acted toward maintaining the storm's angular momentum. Since the outflow of hurricanes normally occurs in the same relative position as in this instance, the location of the clockwise outflow eddy as observed will aid storm growth and maintenance from the momentum viewpoint.

In many situations the main inflow also takes place to the right of the direction of motion, and then the result will be different from that just obtained. It will be of interest in future studies to consider not only the total transport of T_c, but also its detailed distribution with height. If both lower inflow and upper outflow occur to the right of the direction of motion, the centre displacement will act to equalize the angular momentum at all heights. Inflow and outflow to the left would act to produce an increasing vertical shear of v_{θ}, with little change of net vortex strength. Inflow to the left and outflow to the right would contribute to an increase of cyclonic momentum at all heights, and the opposite holds for inflow at the right and outflow at the left.

A complete balance of angular momentum referred to the storm centre cannot be worked out for 2 September, because this requires a volume distribution of data rather than just observations on one surface. It will be of interest, however, to see by means of a rough calculation, how the computed inflow compares with the transport of momentum to the ground by means of surface stresses. Direct calculation would require knowledge of the spatial distribution of v_{θ} at the surface; this information does not exist. We must resort to the stress calculation by Palmén and Riehl (1957) for the mean hurricane; their Fig. 6 yielded a transport of $13{\cdot}6 \times 10^{23}$ g cm^2 sec^{-2} to the ocean surface for the area bounded by the 4·5°-radius. The difference between the mean hurricane and *Ella* consisted mainly in absence of the central core of high speed in *Ella*. Beyond the 2°-radius, the two circulations were quite comparable as far as one can judge. Further, *Ella* was partly over land, some of it mountainous. From Palmén and Riehl, most momentum loss to the ocean occurred outside the 2°-radius in the mean hurricane because of small area and radius of the interior high-speed core. Hence it would seem conservative to assume a transport rate of three-quarters of that for the mean hurricane for *Ella*; the actual transport may well have been larger.

With this assumption, the transfer to the ocean becomes 10·2 units, leaving a net decrease of momentum of 3·8 units. If one assumes that time changes in v_{θ} are independent of the space coordinates, the mean vortex strength would decrease by about 2 kt per day from the fluxes through the cylinder and to the ground. This result should be compared with the actual mean vortex strength on 2 September. On the boundary (Fig. 5) the mean value of v_{θ} was 6 kt. From qualitative inspection of the research flights it is known that v_{θ} did not attain 50 kt except in a limited band in low and middle troposphere, and that at 235 mb clockwise circulation prevailed over the whole interior. From this one

may estimate that the mean vortex strength was certainly well below 20 kt, probably nearer 10 kt. It follows that the computed decrease in vortex strength was a significant fraction of the mean. Actually, *Ella* continued to lose intensity for at least one day after the period of calculation.

5. Conclusion

A fortunate distribution of upper-air observations has made it possible to show the structure of a tropical storm through the whole troposphere at a fixed radius from the centre using synoptic data, and to determine the exchange of heat, moisture and momentum between the storm and its large-scale environment. Considering structure, of particular interest are the maximum of tangential circulation near 700 mb, the strong ageostrophic components of motion with a high level of non-divergence above 400 mb, and the fact that the moisture content of the air was lower where air was moving toward the vortex in the low troposphere than where it was moving away.

Momentum and heat and moisture transport calculations pointed to decreasing vortex strength with time, in accord with the actual sequence of events; it must be noted, however, that the computed heat export was within the margin of error of the computations. While the equations discussed are not prognostic except by means of extrapolation, they nevertheless bring out important boundary effects influencing hurricanes. Considerable additional insight into the mechanisms governing the life cycle of hurricanes will be gained if calculations as here performed can be made successively at various stages of hurricane growth and decay, and if they can also be performed at several cylinders around a storm instead of just a single cylinder.

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Utility of stretch vector correlation coefficients

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(Manuscript received 13 February 1959)

SUMMARY

This paper compares empirical values of the vector stretch correlation coefficient, and the total vector correlation as fundamentally defined. The former is apparently sufficiently accurate when applied to temporal stretch alone, up to three days, but when applied to space stretch it may have little meteorological meaning unless it exceeds about 0·3 in large data samples (about 450 daily observations).

1. INTRODUCTION

Comprehensive summaries and applications of wind-vector statistics have been presented by Durst (1954, 1957). His treatment of linear vector correlation involves coefficients of simple stretch and of simple turn. If **W** is a wind vector with west-to-east component u and south-to-north component v, and **Z** is another wind vector with components x and y defined like u and v, respectively, then Durst's total vector correlation coefficient may be written

$$r = \frac{\Sigma (ux + vy)}{n \sigma_{\mathbf{W}} \sigma_{\mathbf{Z}}} + \frac{\Sigma (xv - uy)}{n \sigma_{\mathbf{W}} \sigma_{\mathbf{Z}}} \quad . \quad . \quad . \quad . \quad (1)$$

where n is the number of paired observations, $\sigma_{\mathbf{W}}$ and $\sigma_{\mathbf{Z}}$ are vector standard deviations, and u, v, x and y are measured from their respective mean values. The two fractions of Eq. (1) are, in order, the coefficients of simple stretch and simple turn. Implicit in Eq. (1) is the assumption that **W** and **Z** bear a fixed angular relationship to one another. This seems a severe restriction for winds considerably separated in time and/or space, but the matter is further complicated by Durst's findings that the turn coefficient is relatively insignificant, i.e. that **W** and **Z** can be assumed parallel. In any event, the stretch correlation coefficient has had much use in studies of wind connectedness, with varying degrees of success.

The classical development of ' correlation ' has been in scalar contexts, and it is by no means clear that this concept will provide the best measure of wind connectedness. However, it is pertinent to study the vector correlation parameter derived from fundamental definitions, if only for use as a measure of statistical and computational efficiencies of other parameters such as Durst's. Court (1958) has applied the fundamental definitions of linear correlation to vectors, showing that the multiple correlation coefficients of each component of one vector upon all components of another are involved. His relation for the total vector correlation of **W** for regression on **Z** is

$$R^2_{\mathbf{W}\,\mathbf{Z}} = \frac{\sigma_u^2 (r_{ux}^2 + r_{uy}^2 - 2 r_{ux}\, r_{uy}\, r_{xy})}{\sigma_{\mathbf{W}}^2 (1 - r_{xy}^2)} + \frac{\sigma_v^2 (r_{vx}^2 + r_{vy}^2 - 2 r_{vx}\, r_{vy}\, r_{xy})}{\sigma_{\mathbf{W}}^2 (1 - r_{xy}^2)} \quad . \quad . \quad (2)$$

where σ is a standard deviation (root-mean-square in the case of wind components), r is a scalar correlation coefficient (covariance divided by the product of standard deviations), and the subscripts indicate pertinent wind components or vectors.

Ellison's (1954) development in tensor notation can be extended to the same result, but Court's treatment should be more readable to meteorologists and is moreover recommended as a comprehensive survey of the problem.

Eq. (1) may be put in analogous form to Eq. (2) by use of appropriate statistical identities :

$$r = \frac{\sigma_u \sigma_x r_{ux} + \sigma_v \sigma_y r_{vy}}{\sigma_{\mathbf{W}} \sigma_{\mathbf{Z}}} + \frac{\sigma_x \sigma_v r_{xv} - \sigma_u \sigma_y r_{uy}}{\sigma_{\mathbf{W}} \sigma_{\mathbf{Z}}} \quad . \quad . \quad . \quad . \quad (3)$$

Note that Eq. (3) is not derivable from Eq. (2). The quantities R and r are unique, and examination of their differences is in order, especially since Durst's work indicates that the stretch term alone in Eq. (3) is suitable for wind comparisons. Since nothing is known about

the sampling distribution of either parameter, empirical methods are in order. In a study of Singapore winds, Scott (1956) found only small differences between Durst's vector stretch correlation and Ellison's vector correlation when applied to time lag. This paper compares Durst's stretch correlation quantity and Court's vector correlation coefficient computed for time and space lags at various pressure altitudes.

Data and method

The data basic to this study are the five-year serially-complete wind collections of the U.S. Weather Bureau (1958) and statistics computed therefrom by Sandia Corporation. These statistics included all the scalar correlation quantities represented in Eqs. (2) and (3), for time, space and both time and space lags. The period of record was from 1 March 1951 to 29 Feb. 1956, and only once-daily winds are involved. Stations included are shown in Table 1.

TABLE 1. Station list

Nome, Alaska	* Green Bay, Wisc.	* Columbia, Mo.	Norfolk, Va.
* Fairbanks, Alaska	* Sault Ste. Marie, Mich.	* Rantoul, Ill.	Charleston, S. C.
Anchorage, Alaska	Mt. Clemens, Mich.	* Dayton, Ohio	* Tucson, Ariz.
Whitehorse, Yukon T.	Buffalo, N. Y.	Pittsburgh, Pa.	Midland, Texas
* Annette, Alaska	Maniwaki, Que.	* Washington, D. C.	Lake Charles, La.
* Edmonton, Alberta	Rome, N. Y.	Hempstead, N. Y.	Burrwood, La.
* Seattle, Wash.	* Caribou, Maine	Nantucket, R. I.	Montgomery, Ala.
* International Falls, Minn.	* Medford, Oregon	Long Beach, Calif.	Jacksonville, Fla.
Boise, Idaho	* Oakland, Calif.	Albuquerque, N. Mex.	* Brownsville, Texas
Great Falls, Mont.	* Ely, Nevada	Ft. Worth, Texas	* Miami, Fla.
* Bismarck, N. D.	* Denver, Colo.	* Little Rock, Ark.	* Lihue, T. H.
* St. Cloud, Minn.	* Dodge City, Kans.	Nashville, Tenn.	* San Juan, P. R.
	** Omaha, Nebr.	Greensboro, N. C.	* Albrook, C. Z.

In the comparisons given below, time-lag correlation quantities were computed for all stations in Table 1. For space or space-and-time correlation quantities, only the stations indicated by asterisks were included, with **Z** taken in each case as the wind at Omaha, Nebraska. Durst's simple stretch correlation coefficient (i.e., only the first fraction of Eq. (3)) was plotted against Court's R on equi-scale Cartesian co-ordinates as shown in Figs. 1 to 4.

3. Discussion and conclusions

As was to be expected, the total vector correlation coefficient R is consistently larger than the vector stretch correlation coefficient r. Major disagreement between r and R would be expected for all negative values of r, since R is defined as positive, but Figs. 3 and 4 show major disagreements for r positive and small. For correlation in time, it is apparent that there is little gained by use of the computationally cumbersome R, at least for most meteorological applications. For correlations in space or space and time, however, r appears to be spurious when it is less than about 0·3. This applies to correlation quantities computed from data samples of comparable size to these used here ; i.e., more than 450 daily data pairs involved in each scalar correlation coefficient. For smaller samples, it is quite likely that the threshold value of r for important discrepancy with R is larger than 0·3. Unfortunately statements concerning the statistical significance of R and r cannot be made, although it can be shown that the scalar correlation coefficients used in this study are all highly significant when they exceed about 0·3 (Charles 1959). In the demonstration, it appears that the collection of 450 successive daily winds is equivalent to about 50 to 100 independent observations.

Until more is known concerning the sampling distributions of both parameters, it seems valid to conclude that Durst's vector stretch correlation coefficient may properly be applied to problems of wind connectedness in time and/or space, provided it is quite large. When it approaches 0·3, and if the applications involve explanation of vector variance, the total vector correlations defined by Court or Ellison should be more meaningful.

The difficulties of interpretation discussed can of course be avoided by applying correlation methods to the zonal and meridional components of the winds separately.

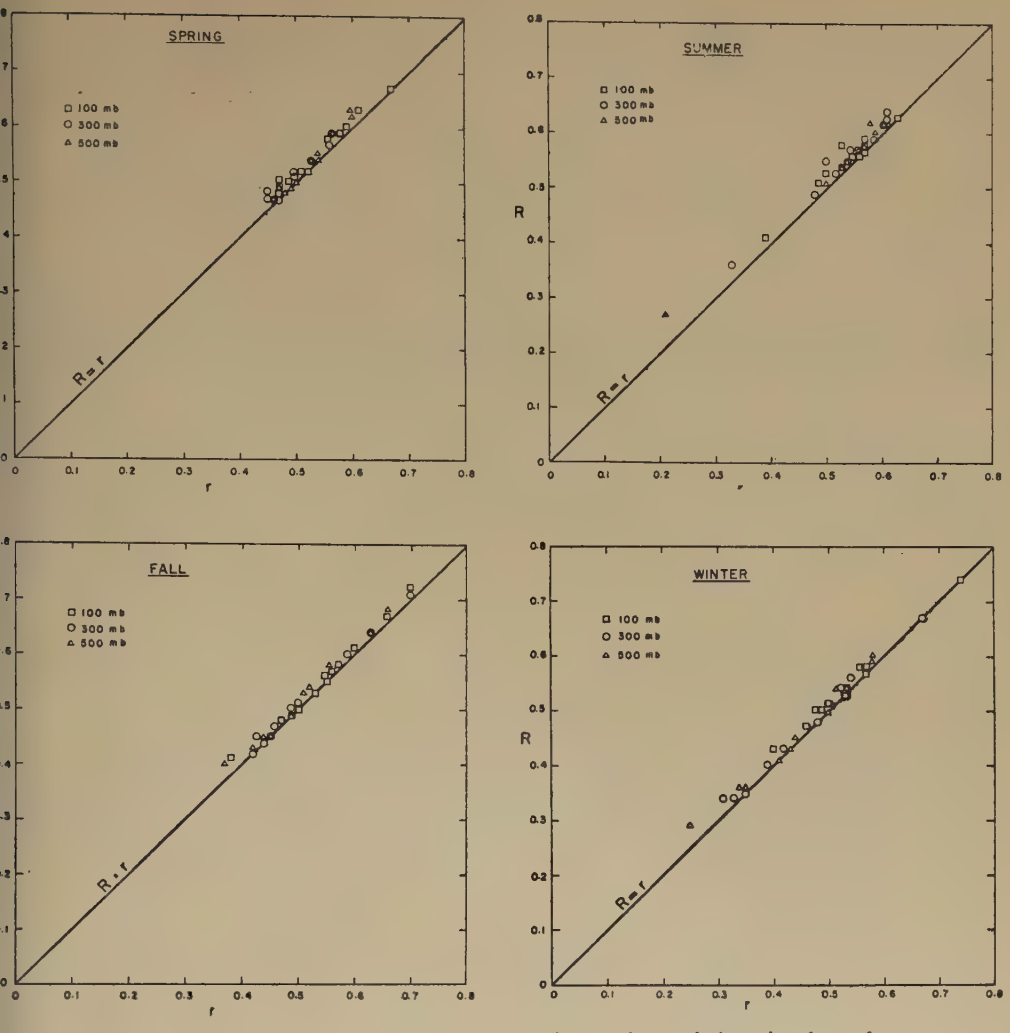

Figure 1. Total vector correlation versus simple stretch correlation, time lag 1 day.

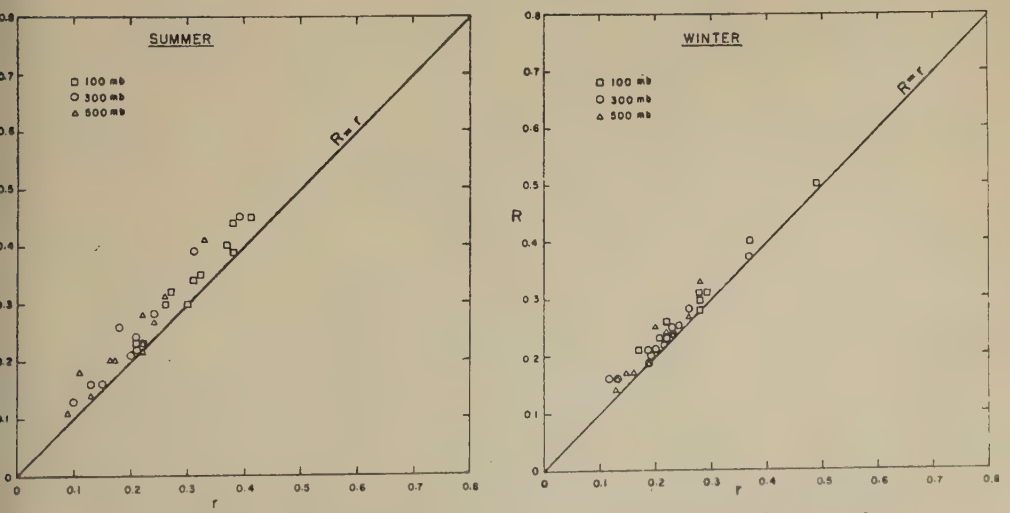

Figure 2. Total vector correlation versus simple stretch correlation, time lag 3 days.

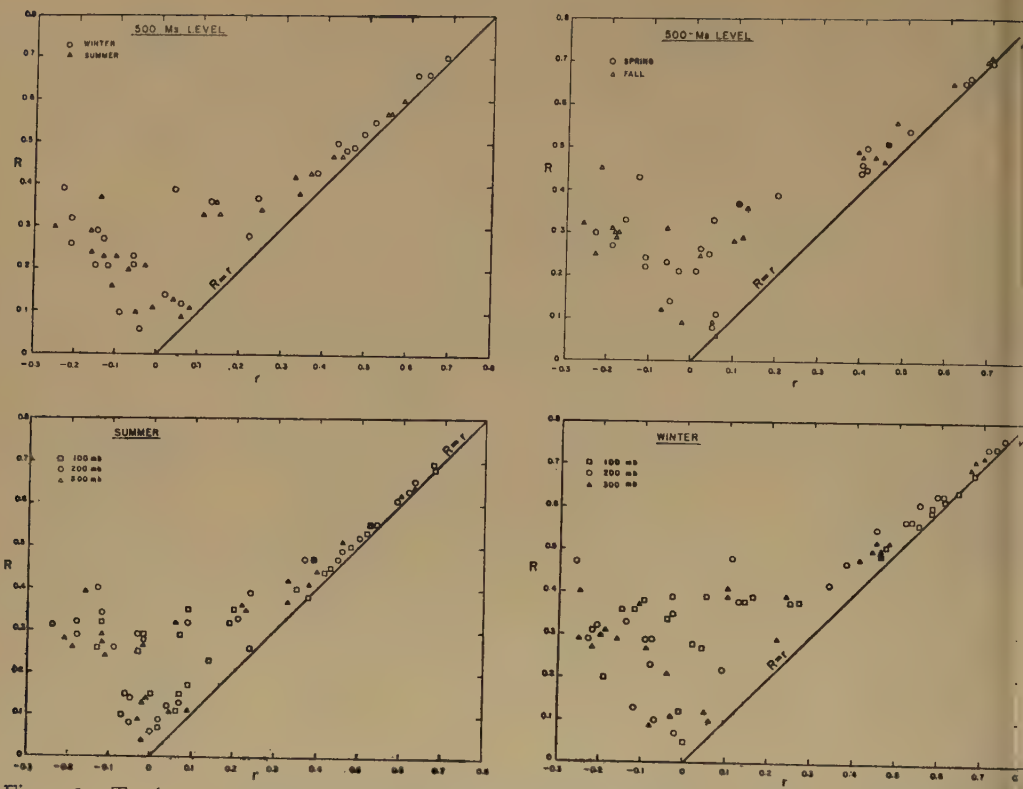

Figure 3. Total vector correlation versus simple stretch correlation, space separation. Omaha, Nebraska taken as master station; zero time lag.

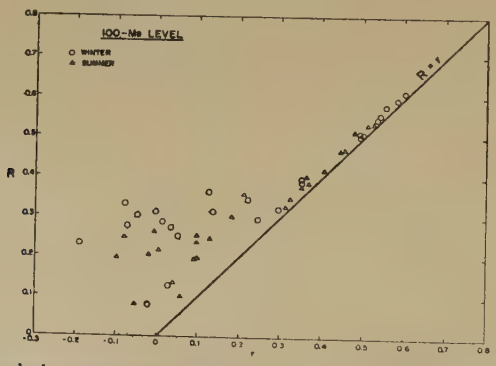

Figure 4. Total vector correlation versus simple stretch correlation for both time lag and space separation Omaha, Nebraska, taken as master station; time lag 1 day.

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551.501.7 : 551.507.321.2

A method of determining the constant in the balloon-ascent formula

By K. L. SINHA
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(Manuscript received 28 August 1958; in revised form 27 November 1958)

Summary

Expressing the coefficient q, of the rate-of-ascent formula of the balloon (e.g. $V = q\,F^{\frac{1}{2}}/(W+F)^{\frac{1}{3}}$, where V is the rate of ascent of the balloon, W the weight of the balloon and F the free-lift) in terms of the coefficient of aerodynamic resistance κ of the balloon, a curve of q as a function of the Reynolds number N is worked out. Introducing a $\kappa N^2 - N$ curve, the value of q, appropriate to a balloon flight is obtained.

1. Introduction

Rubber balloons, filled with hydrogen gas, are extensively used for determination of the upper winds and base of low clouds. The rate of ascent is worked out at many places by the formula

$$V = q\,\frac{F^{\frac{1}{2}}}{(W+F)^{\frac{1}{3}}} \qquad . \quad . \quad . \quad . \quad (1)$$

where V is the rate of ascent of the balloon, W the weight of the balloon and F the free-lift weight. q is a constant for balloons of more or less same sizes and rates of ascent but it differs with the variation in the sizes of the balloons with different rates of ascent.

The appropriate values of q which are to be employed in the above formula for finding the rates of ascent of the balloons are obtained experimentally by making a series of measurements of V by means of a theodolite, corresponding to the values of F and W. This seems to be the only method at present for determining the value of the unknown quantity q of Eq. (1). It is proposed here to work out a process by which it seems possible to determine the value of q, appropriate to the balloon flight, in a different way.

2. Expression for q in terms of coefficient of aerodynamic resistance

The uniform vertical velocity V of the balloon can also be expressed (Sinha 1957, 1958) by the equation

$$V^2 = \frac{Fg}{\rho d^2 \kappa} \qquad . \quad . \quad . \quad . \quad . \quad (2)$$

where F is the free lift, g the acceleration due to gravity, ρ the air density, d the diameter of the inflated balloon and κ the coefficient of aerodynamic resistance which is a function of the Reynolds number Vd/ν; ν being the coefficient of kinematic viscosity.

Comparing Eqs. (1) and (2) and taking the density of the hydrogen gas in the balloon as one-fourteenth of that of the surrounding air, q can be expressed as

$$q = g^{\frac{1}{2}}\,(\tfrac{1}{8}\tfrac{3}{4}\,\pi)^{\frac{1}{3}}/\rho^{\frac{1}{6}}\,\kappa^{\frac{1}{2}} \qquad . \quad . \quad . \quad . \quad (3)$$

If the rate of ascent of the balloon is obtained in km hr^{-1} the value of q will be given by :

$$q = 0{\cdot}89/\rho^{\frac{1}{6}}\,\kappa^{\frac{1}{2}} \qquad . \quad . \quad . \quad . \quad . \quad (4)$$

3. Variation of q with Reynolds number

It is seen from Eq. (4) that the value of q depends inversely as the second root of the coefficient of aerodynamic resistance and as the sixth root of the air density. The variation of air density has therefore comparatively less effect on the value of q than that of the coefficient of aerodynamic resistance. As the value of the coefficient of aerodynamic resistance κ varies with the Reynolds number N, the value of q will vary with the Reynolds number. The q-N variation curve for certain air density will depend upon the values of κ at different Reynolds numbers.

There are some difficulties in obtaining the values of κ at different Reynolds numbe because the values obtained by different methods of various workers (Cave and Dines 191 Brazier 1921, Horiguti 1923, Ludlam 1953, and others) are different. Saha (1956) has reproduce the curves showing the variation of the coefficient of aerodynamic resistance with the Reynol number on the basis of the data of different workers. The author (1958b, 1958c) has observe that the mean of the values of the coefficient of aerodynamic resistance of balloons at differe Reynolds numbers, represented by Saha (1956) for the rising and tethered balloons provid workable values of the coefficient of the aerodynamic resistance at different Reynolds numbe Using these values of the coefficient of aerodynamic resistance, Sinha (1959) has constructed wit the help of Eq. (4), a curve showing the variation of q with the Reynolds number. The valu of the coefficient of aerodynamic resistance from the curves under reference are more or le systematic to each other up to the lower limit of the Reynolds number of $0{\cdot}7 \times 10^5$, the mea values of the coefficient of aerodynamic resistance have been taken up to this lower limit the Reynolds number for the above purpose. As mentioned earlier, the value of q is n much affected by small changes in the air density. The curve for q-N has been drawn for a density of ·00115 g cm^{-3} and it has been indicated how the values of q are obtainable for larg differences of air density.

4. Difficulty of determining the value of q appropriate to the balloon flight

Although it is possible by the above process to find the value of q at different Reynol numbers from the above-mentioned q-N curve, there is a difficulty in finding the value of appropriate to the balloon flight from the curve under reference, because the Reynolds numbe corresponding to a balloon flight for which V is to be determined is not directly available, a the Reynolds number itself depends upon V. Other steps are necessary to solve this difficult before the curve under reference can be utilised for finding the value of q appropriate to th balloon flight.

5. Determination of κN^2 appropriate to the balloon flight

It can be shown that

$$\kappa N^2 = Fg/\rho\nu^2 \quad . \quad . \quad . \quad . \quad . \quad (5$$

F, g, ρ and ν in Eq. (5) being known or determinable parameters, it is possible to determin the value of κN^2 appropriate to a balloon flight. Thus, although the value of N correspondin to a balloon flight is not directly known, that of κN^2 corresponding to a balloon flight is know and it would be possible also to find N corresponding to a balloon flight if a $\kappa N^2 - N$ curv can be constructed.

6. The $\kappa N^2 - N$ curve

The values of κ at different Reynolds numbers being known, the values of κN^2 can be worke out for different Reynolds numbers and as such a curve can be constructed representing th relationship between κN^2 and N. The value of κN^2 corresponding to a balloon flight bein determinable, it becomes possible from this curve to determine the value of N appropriate t the balloon flight.

7. Combination of q-N and $\kappa N^2 - N$ curves

The combination of the q-N and $\kappa N^2 - N$ curves thus provides a means of finding th value of q appropriate to a balloon ascent.

The relevant values of κ, κN^2 and the computed values of q for air density of 0·00115 g cm^{-} at different Reynolds numbers are given in Table 1.

TABLE 1. Values of κ, κN^2 and q at different Reynolds numbers

Reynolds number $(N) \times 10^{-5}$	0·7	1·0	1·25	1·50	1·75	2·0	2·25	2·50	2·75	3·0	3·25	3·50	3·75	4·0
Value of κ	0·31	0·28	0·25	0·23	0·21	0·18	0·17	0·15	0·15	0·13	0·13	0·12	0·12	0·1
Value of $\kappa N^2 \times 10^{-10}$	0·15	0·28	0·39	0·52	0·64	0·72	0·86	0·94	1·13	1·17	1·37	1·47	1·69	1·9
Computed value of q	4·9	5·2	5·5	5·7	6·0	6·4	6·6	7·1	7·1	7·6	7·9	7·9	7·9	7·9

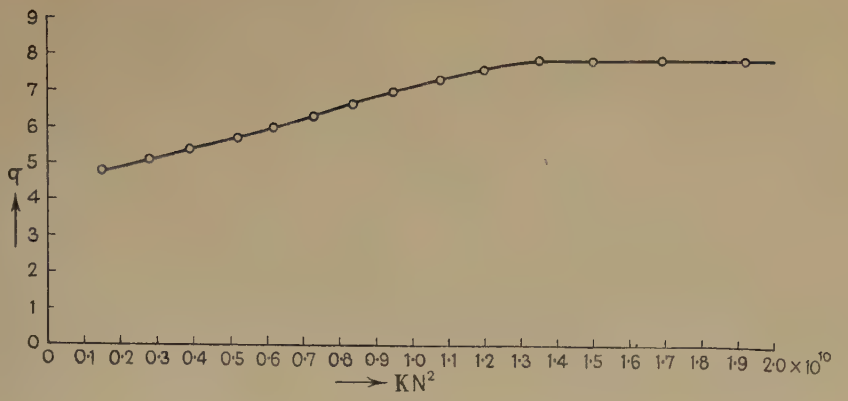

Figure 1. Variation of q with κN^2.

Combining the corresponding q-N and $\kappa N^2 - N$ curves, obtained from the data in Table 1, curve depicting the variation of q with κN^2 is constructed in Fig. 1 which provides directly he appropriate value of q from the knowledge of the value of κN^2 corresponding to the balloon light.

8. Some check on the value of q from q-κN^2 curve

A few measurements were made with the balloons used for day-to-day pilot-balloon bservations. The value of q which is used for these balloons is practically 5·0 when the weight f the balloon and the free-lift are expressed in grammes and the rate of ascent in km hr^{-1}. From he known or determinable data values of κN^2 for the balloons used were worked out. Values f q corresponding to values of κN^2 were found from the q-κN^2 curve. Values of q obtained rom the q-κN^2 curve were in good agreement with the average value of q which is used in daily ork and is based on a long series of observations of pilot balloons using the theodolite method.

A few experimental determinations of q were also made in the case of the large balloons sed for the radiosonde-rawin observations, working out V from the pressure and temperature lata of the radiosonde records using Eq. (1). Values of q thus obtained are, however, approximate nd they ranged mostly from 8·1 to 8·7. The diameters of the inflated radiosonde-rawin balloons re more than 200 cm and the rates of ascent more than 20 km hr^{-1}. Values of the Reynolds number, orresponding to these big sizes and high rates of ascent of these balloons, are higher than $\times 10^5$. The value of q found for these balloons corresponds to the portion of the curve in ig. 1 when the value of q remains constant, and is approximately 8. This again shows that the alue of q derived from the curve under reference is comparable with the experimentally determined alue of q at higher Reynolds numbers also.

9. Conclusion

It would seem that a combination of the q-N and $\kappa N^2 - N$ curves, resulting in the q-κN^2 urve can provide a means of finding the value of the constant of the balloon-ascent formula, ppropriate to the balloon flight.

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551.515.1

Some measurements on undercutting cold air

By F. A. BERSON

(Read 21 January 1959. Presented by Mr. M. K. Miles. See *Q.J.*, **84**, p. 1)

Dr. R. S. Scorer : If the earth's rotation is neglected it must be assumed that the componer of velocity of a particle of air across the coast must remain constant all along its track : I doub whether this is justified because the phenomenon represents a rather sudden invasion of cold ai

Mr. H. H. Lamb : Is the lack of observations over the sea really insuperable ? An aircra reconnaissance flight, if such could be arranged, at least in some sample cases for investigatio of the ' cool change,' should make it possible to know the temperatures and humidities in th different air-bodies involved as well as surveying the alignment of the phenomena whilst sti over the sea. This might be a justifiable procedure to investigate such an important element c the climate of southern Australia.

Dr. R. C. Sutcliffe : The phenomenon has clearly something in common with an ordinar sea-breeze where the progress of the ' front ' may be much slower than the inflow across th coast. Continuity requires the cool sea air to undergo convergence and presumably to mix wit the heated land air near the sea-breeze front. The problem is complicated dynamically and thermo dynamically and in the case of the ' cool change ' there are the pre-existing thermal (solenoidal field, the changing thermal field due to the rapid heating of the inflowing sea-air, the discontinuit in surface friction across the coast line and the response to Coriolis acceleration. It is unlikel that any of these can be ignored in a quantitative theory of the phenomenon.

Mr. C. E. Wallington : The friction-head form of the advancing cold air reminds me c the shape of the sea-breeze frontal structure as revealed by gliding flights over Hampshire Occasionally these fronts penetrate well inland from the south coast and their structure is easil discernible by the accompanying patterns of vertical motion, cloud and haze distributions Some study along the lines of Dr. Berson's technique could well be carried out in this country

Dr. R. C. Rainey (*partly communicated*) : These ' cool changes ' in southern Australia ar closely paralleled in South Africa, where, for example, wind-surges originating on, or related t sea-breeze fronts similarly affect the hinterland more than 100 mi from the coast (*Q.J.*, **74**, p. 199) and where also such a surge commonly precedes the cold front at which an airmass from highe latitudes advances along the coast. Evidence of the frequent development of such a wave o the coastal front, travelling 15 to 35 mi hr^{-1} along the 600 mi from Mossel Bay to Durban, 5 to 2 hours ahead of the cold front of a passing depression centred south of the continent, was provide by war-time hourly synoptic observations (Van Lingen 1945, *S.A.A.F. Met. Sect. Tech. Note* No. 33).

An analysis of gliding flights at a cold front during its subsequent passage across the interio of South Africa (*Q.J.*, **73**, p. 437) indicated a localisation of previously scattered convectiv up-draughts in the unstable warm air into a narrow but apparently continuous zone immediatel ahead of the advancing cold air. Did the observations of vertical air velocity in the vicinity o these Australian discontinuities provide any evidence of a similar effect ?

Mr. M. K. Miles (*in reply*) : As Dr. Sutcliffe remarks the progress of sea-breeze ' fronts may be slower than the inflow across the coast, and the author quotes results obtained b Koschmieder for sea-breeze ' fronts ' on the Baltic Coast showing that the rate is about half th speed of the cold air.

Dr. F. A. Berson (*in reply, communicated*) : I wish to thank Mr. Miles for presenting m paper.

With regard to Mr. Lamb's suggestion, flights by the R.A.A.F. were made over th Southern Ocean during the war and on a few occasions later, but the data were not suitable fo studying frontal phenomena. During the 1954-1955 season, meteorographs were mounted on commercial aircraft plying over Bass Strait and records from flight sequences revealed persistenc and slow intensification of a coastal front over the sea ahead of an approaching major cold front The results have since been published.

I agree with Dr. Sutcliffe on most points he has raised. One has already been taken up b Mr. Miles. As to the heating effects, we had in fact attempted to assess the rate of heating in th invading sea air and its influence on frontal movement, applying the theory by Dr. F. K. Bal

Q.J., **82**, p. 15). Prior to revision my paper contained a paragraph on this. Effects of the diurnal cycle of convection over land were also studied. Admittedly a dynamic theory of coastal surges was not attempted : analysing the ' head ' of the cold air and comparing it with the hydraulic friction head rather emphasized the importance of mixing in the frontal zone, of the cool sea-air and the heated land-air. Dynamic similarity cannot be complete and the term indicates merely a method of analysis. These remarks should also cover Dr. Scorer's comments.

As the observations from gliding flights mentioned by Mr. Wallington and Mr. Rainey were made well inland they are comparable with those of penetrating sea-breezes and surges in Australia studied by Mr. Clarke and Mr. Reid. In reply to Dr. Rainey's question, the frequency of our pilot-balloon ascents ahead of the first discontinuity was not adequate to show an organization of up-currents as described by him, but similar effects have been observed by sailplane pilots in Australia, and on one occasion we obtained a series of time-lapse photographs which show clearly a belt of cumulus advancing with the first windshift. Strong ascending motion just behind the first windshift, as shown in Fig. 8 of the paper, could, however, correspond to up-draughts immediately ahead of the advancing cold air observed by Dr. Rainey, since, further inland, that windshift might be weak and pass unobserved.

551.510.52 : 551.515.82 : 551.557.5

Temperature, humidity and cloud near fronts in the middle and upper troposphere

By J. S. SAWYER

(Read 18 February 1959. See *Q.J.*, **84**, p. 375)

Dr. R. S. Scorer : I think it is instructive to think of the direct circulation at the jet entrance as supplying the energy for the jet stream by releasing potential energy. The convergence and divergence at the top and the bottom are consequences of it. What is interesting is the additional region of divergence indicated in Mr. Sawyer's Fig. 8.

A full explanation cannot omit the potential energy released by condensation. This enables the upflow to continue without substantially altering the temperature distribution which produces it. The main temperature changes therefore occur in the sinking air.

Prof. R. G. Fleagle : Mr. Sawyer has been too modest in his presentation. The evidence that a large proportion of fronts are dry in the middle troposphere and that they are formed presumably as consequences of the dynamics of large-scale depressions utilizes concepts quite different from those of the old cyclone-theory of the Norwegians. It is not enough to say that this paper and others in a considerable line merely modify the details of the Norwegian model. They attack the Norwegian model at two points : the concept of cyclogenesis resulting from instability of a pre-existing frontal surface and the concept of the ' clash of air-masses ' or the upgliding above frontal surfaces. These are essential features of the Norwegian model, and I think we should not insist on accommodating upper-air measurements of the sort Mr. Sawyer has presented with the old model.

Nor is it enough to say that the features which Mr. Sawyer has described are already known to those who have carefully analysed upper-air data, though broadly this is true. For so long as meteorological texts are published which presented frontal structure as a closed subject even before the development of the radiosonde, we must expect students to be confused in comparing textbook concepts with atmospheric data.

Finally, I should like to ask Mr. Sawyer a question. Do you regard the record of small-scale variability, amounting to a degree or so, as a reliable record of the actual temperature encountered by the aircraft ? If so, what sort of structure and what field of motion do you suppose accounts for this variability ?

Dr. J. M. Stagg : As usual in Mr. Sawyer's papers the physics and theory of this paper are unexceptionable, but I am not quite convinced that he had a sure enough foundation to build them on. According to his Fig. 6 the depression of the frost point at 500 mb is no more likely to be low at the front than it is 200 mi on either side of it, and the individual cases he gives us are not more reassuring. But perhaps Mr. Sawyer has many more cases up his sleeve.

DR. R. C. SUTCLIFFE : It is unfortunate that time has allowed Mr. Sawyer to present onl his recent *Quarterly Journal* paper which deals with but a limited aspect of a subject of grea importance to which Mr. Sawyer has made major contributions in *Geophysical Memoi Meteorological Office No. 96, 1955*, and in *Proceedings of the Royal Society, 1956*. I spoke mysel on the subject at an international symposium in Bergen last year, showing a number of fronta cross-sections for which Meteorological Research Flight results were available. There was lively discussion. There is no doubt that a new concept of frontal regions, truly dynamical i character, is replacing the classical upslide model, largely intuitive and descriptive.

Naturally, frontogenesis and frontolysis are not new topics but the three-dimensional structur which must arise in the formation of a frontal-jetstream system (looked upon as a problem o dynamical development) has not been worked out quantitatively. Mr. Sawyer's own work i the Royal Society paper to which I referred is an important beginning. The development of th strong upper winds must be by ageostrophic flow down the gradient of pressure and to develo a wind of 200 kt the air must have moved some 500 mi in this way. Thus the existence of frontal-jetstream system implies that a very large overturning and distortion must have occurre with subsidence as well as ascent. It is not difficult to infer a plausible model which is dynamicall reasonable and which accounts for the dry tongue (as was sketched on the blackboard). The shar discontinuities in lapse-rate and horizontal temperature gradient which mark the two boundarie of the front, as conventionally analysed in most recent frontal sections, require special explanatio in terms of smaller-scale dynamics probably including turbulent diffusion. This hyperbaroclini zone is not essentially either an upslide or a downslide surface.

MR. D. G. HARLEY (*communicated*) : I do not wish to discuss Mr. Sawyer's conclusion from his observations, but only the relation of his points to those the forecaster deals with. A first sight this paper is rather upsetting to the forecaster, because of its description of a dry zon at 500 mb. General experience is that many active fronts do have cloud at 500 mb and higher Clearly it depends on what one calls the front. The definitions in the textbooks have graduall changed over the last 20 years from, essentially, the boundary between two airmasses of differen characteristics, to a sloping surface of density change. Mr. Sawyer has used the latter an demonstrated how the front is often only a subsidence inversion. Dynamically, the temperatur change is no doubt the main thing, but in dealing with clouds one still has to distinguish, b means of conservative measures of humidity, between air-mass boundaries and subsidenc inversions. Comparison of the profiles of temperature and frost-point depression in this pape shows that in several cases (29 Nov. 1954, 27 April 1951, 24 Nov. 1953, 11 Jan. 1955) th pseudo-potential wet-bulb temperatures rose markedly on the warm side of the front as marked at about 70 naut. mi at 500 mb and quite close to it at 600 mb.

The concept of fronts is no more than a useful working tool which sums up some typica features of the atmosphere. As such it is a rather hazy but very useful idea. It does not seem t me that anyone gains by narrowing the definition of a front to temperature alone. On the othe hand, the working forecaster would lose. He has to keep in mind all aspects of the comple motions of the atmosphere, but he cannot do without the front as an air-mass boundary.

MR. J. S. SAWYER (*in reply*) : I fully agree with Dr. Scorer that the latent heat released b condensation plays an important, perhaps an essential, part in the dynamics of active fronts However, the effect is greatest in the lower troposphere where the saturated adiabatic lapse rat differs most from the dry adiabatic lapse rate. In the upper troposphere the difference is smaller and it may be possible to describe the essential mechanism of circulation around the jet strea without considering condensation.

In reply to Prof. Fleagle, it is my view that irregularities of 1°F (or sometimes 2°F) ma arise from the difficulties of observing and of flying an aircraft on a specified isobaric surface However, there are irregularities which are greater than this, particularly near clouds. Some o these arise from complications introduced by condensation and precipitation; others may be du to small-scale motion such as gravity oscillations.

As Dr. Stagg remarks, the observations reported in my paper do not show a clear-cu common pattern of temperature and humidity accompanying each front That is why I hav reproduced all the available data for 500 and 600 mb. I do not regard the averages shown i Fig. 6 of my paper as very reliable, particularly towards the edges of the diagrams where th number of cases become fewer, and I prefer to base my idea of a typical humidity distributio upon inspection of the humidity profile in the few cases of frontal zones well defined by temperature

The new ideas on fronts to which Prof. Fleagle and Dr. Sutcliffe refer do not, of course affect the idea that a front is an air-mass boundary in the sense that air from widely differen areas comes into juxtaposition. However, I think that it is wrong to try and pick out one distinc

boundary surface on the basis of wet-bulb potential temperature or any other criterion, because here is no physical process which produces two essentially different air masses side by side but only dynamical and physical processes which concentrate the initial gradients of temperature and humidity into relatively narrow zones (not necessarily a single zone). It is the task for research to describe these zones and their relations with cloud belts and precipitation. A truer picture will, I hope, gradually emerge which will be found more useful to the forecaster than that of a simple air-mass boundary.

551.513.1 : 551.557.2 : 551.558.21

Long waves, lee waves and gravity waves

By F. K. BALL

(Read 18 February 1959. Presented by Mr. G. A. Corby. See *Q.J.*, **85**, p. 24)

DR. R. S. SCORER : This paper shows how absurd the term ' blocking high ' is. The stationary eddies in Long's model experiments could not be described as ' blocking ' the flow : they are produced in it by something else, in this case a hump on the bottom, and there is probably some analogous disturbance producing ' blocking highs.' Lee waves are not analogous, although the equations are, because the boundary conditions are not analogous. There is a coupling of the flow at all heights by gravity which relates the top and bottom boundaries, only one of them being rigid. In Long's experiments, conditions were imposed at the two boundaries independently.

PROF. R. G. FLEAGLE : There is evidence from the dishpan experiments and from theory that the development of a jet stream is an essential feature of a baroclinic atmosphere under certain conditions. Dr. Ball's paper implies, because his atmosphere is constrained to move horizontally, that development of jet streams is not essentially a baroclinic phenomenon. There may not actually be a contradiction here, but there surely is a paradox. Can the paradox be resolved ?

MR. J. S. SAWYER : As Dr. Fleagle points out, the jet stream maximum near the tropopause level is associated with a strongly baroclinic zone and must be an essentially baroclinic phenomenon. However, if the atmosphere were barotropic, it might still be that it would develop local concentrations of flow rather like jet streams as Dr. Ball's paper suggests. If similar confluence of flow from north and south developed in a baroclinic atmosphere (for reasons similar to those appropriate to a barotropic atmosphere) the regions of confluence would also become regions where the north-south temperature was intensified and a baroclinic jet stream would form.

MR. G. A. CORBY (*in reply, partly communicated*) : Whether or not a jet splits into two branches is, according to the theory, determined only by the Froude number of the flow and not by the nature of the disturbing influence. However, if the jet does split, then naturally the amplitude, etc., of the rotors (or of the ' blocking systems ' in the synoptic analogy) is dependent on the source of the disturbance.

Whatever explanation we invoke to account for jet streams and long waves in the atmosphere, it remains of considerable interest that the effect of the latitudinal variation of Coriolis parameter on atmospheric flow can be simulated by density stratification in a liquid model of the type studied by Long.

DR. F. K. BALL (*in reply, communicated*) : I wish to thank Mr. Corby for reading this paper in my absence.

I agree with Dr. Scorer that a ' blocking high,' is the result rather than the cause of a disturbance in the zonal flow. However I do not agree that the term ' blocking high ' is therefore necessarily absurd. It seems reasonable to use the term to describe a certain type of high associated with blocking situations. In the southern hemisphere such highs occur mainly just to the east or southeast of the three main land masses i.e., Australia-New Zealand, South America and South Africa (Van Loon, *Notos*, **5**, 1956, p. 171), indicating that under certain conditions of zonal flow the disturbing influence of a land mass will result in a block.

Mr. Sawyer has, I think, largely resolved Dr. Fleagle's paradox. I would however like to amplify his remarks a little. It has been known for some time that jet streams can occur in an ideal barotropic atmosphere. For instance Neamtan (*J. Met.*, **3**, p. 53, 1946), found exact solutions of the barotropic vorticity equation for a spherical earth which, when the amplitude of the waves is sufficiently large, give jet patterns similar to those discussed in this paper (Neamtan

does not mention the jet systems implied by his solutions, he is mainly concerned with the velocit of the waves). It is clear that, if a slight temperature gradient is present, the dynamic processe which result in the concentration of streamlines to form a jet will also result in the concentratio of isotherms to form a strong horizontal temperature gradient. Baroclinic processes will the doubtless further modify the flow to produce a typical baroclinic jet. It is my belief that som though perhaps not all, of the jets in the atmosphere are formed in this way.

551.574

Ice-nucleating properties of some natural mineral dusts

By B. J. MASON and J. MAYBANK

(Read 18 February 1959. See *Q.J.*, **84**, p. 235)

MR. R. G. VERYARD : I would like to ask whether the nucleating properties of smoke-pollutio particles have been examined. Recently, during cold, smoggy conditions in Liverpool ther was a light fall of snow in the city but not in the surrounding countryside – contrary to wha one would expect in view of the heating of buildings, etc. This is not an isolated case; simila instances have been reported in other towns.

DR. H. L. PENMAN : The laboratory experiments have, presumably, been done at atmospheri pressure, whereas the natural phenomena occur at a much lower pressure. Is this likely to b important ?

DR. R. S. SCORER : Are we to imagine that the special nuclei which can be ' taught ' to freez drops are always able to do it at high temperatures or are those in freshly rising air incompeten until they have been made to do it once ? The latter seems likely because ice-supersaturate air is common.

Finally, can any of the ' taught ' nuclei produce ice crystals at below water saturation ?

PROF. P. A. SHEPPARD (*President*) : With what confidence may the results on pre-activatio be extrapolated in time ? For example, is such pre-activation likely to be effective over period of hours or days in the atmosphere ?

DR. B. J. MASON : In reply to Mr. Veryard, we have not investigated the nucleatin properties of smoke particles but there is no evidence to suggest that ice nuclei are *generall* more abundant in industrially-polluted air. However, certain industrial processes, e.g., smelting produce metallic oxides and sulphides, some of which we have found to be quite effective a ice nuclei.

In answer to Dr. Penman, the efficiency of the nuclei is not likely to be materially altere at reduced pressure, although the rates of growth and evaporation of the ice will be slightl affected because the diffusion coefficient of water vapour varies inversely as the total pressure

In reply to Dr. Scorer, some of the nuclei which can be ' taught,' e.g., kaolinite, are quit efficient even in their untutored state but improve after training. Others, such as montmorillonite are quite incompetent until they have been pre-activated and thereupon improve greatly. Som of the ' trained ' natural nuclei and also a number of artificial nuclei, e.g., silver iodide, lead iodide cupric sulphide, can produce ice crystals in water-sub-saturated air providing the supersaturatio relative to ice exceeds a critical value for the particular substance, usually about 10 per cent.

Professor Sheppard raises the important question : " For how long is the activity of th preactivated nuclei retained ? " Since the publication of our paper we have investigated thi matter further. Samples of both kaolinite and montmorillonite were dried in a storage chambe for periods of up to 30 min between pre-activation and testing. The number of active particles counted after they had fallen into supercooled sugar solution and expressed as a fraction of th total number of particles, determined by sedimentation on a slide, was plotted as a function o the drying time to produce a decay curve in a manner similar to that recently reported by Da (*Proc. Phys. Soc.*, **72**, p. 296, 1958). About 1 per cent. of the kaolinite particles could be pre activated. Their activity decreased exponentially with time so that only about one-tenth survive drying for 30 min at 80 per cent. relative humidity with respect to ice. The decay curve fo montmorillonite shows that 10 per cent. of the particles can be pre-activated and that dryin at 80 per cent. relative humidity causes an initial ten-fold decrease after 15 min but very littl further decay during the next 20 min.

Day's result that unspecified clay particles decayed about 10-fold after one minute's exposure to 80 per cent. humidity may, perhaps, be attributed to the fact that, in his experiment, the ice was rapidly deposited during a violent adiabatic expansion, whereas in our case it was formed much more slowly in a mixing-cloud chamber. The rate of decay does appear to depend upon the manner in which the ice is laid down. On kaolinite the water appears to be retained in surface cavities whereas in montmorillonite it is absorbed in the lattice which expands to accommodate it. In the latter case the ice is firmly bonded and will therefore be more difficult to evaporate.

Having been unable to extend these observations to periods longer than ½ hr, we cannot give a definite answer to Prof. Sheppard's question but we think that, in the case of montmorillonite at least, some pre-activated nuclei may survive for several hours.

551.513 : 551.515

The southern westerlies : a preliminary survey; main characteristics and apparent associations

By H. H. LAMB

(Read 18 March 1959. See *Q.J.*, **85**, p. 1)

Prof. R. G. Fleagle : It would be interesting to know whether the difference in the large-scale circulation of northern and southern hemispheres is to be attributed to difference in topography or to the smaller latitudinal temperature gradient of the northern hemisphere which arises from heat transfer through the arctic ice-sheet. Unfortunately, the qualitative effect of each of these differences is likely to be stronger westerlies in the southern hemisphere so that they offer no clue to an answer. However, a stronger latitudinal temperature gradient also should be accompanied by more rapid development of individual cyclones and anticyclones and by larger and/or more intense systems. The difference in topography of the two hemispheres probably should not have this effect.

Therefore, comparison of the rate of development, the size, and the intensity of cyclones in the two hemispheres might provide insight into the relative importance of topography and latitudinal temperature gradient in accounting for the difference which Mr. Lamb has discussed. I should like to ask Mr. Lamb whether he can compare the rate of development and intensity of cyclones in the two hemispheres ?

Mr. L. C. W. Bonacina : I think Mr. Lamb has contributed a valuable paper in emphasizing the important part played by geographical factors in the genesis of weather and climate.

I am particularly interested in his reference to the southern westerlies as influencing the oceanic circulation of the whole globe, and to the possible effect of variations in the strength of this powerful wind system on the width of the equatorial rain-belt. There is an obvious connection between the equatorial rain-belt and the vertical, or nearly vertical, sun, since it follows with some lag the sun's seasonal course and forms over that part of the globe where, on theoretical grounds, convection should be most active. But I have never been able to understand why the equatorial rain-belt should be so narrowly restricted to a width of not more than some 500 mi. on an average with allowance for monsoon and similar disturbances.

Perhaps my fallacy lay in over-stressing the effect of the vertical sun in initiating the general circulation and under-stressing the speed with which the other wind and pressure systems, trades, westerlies, etc., come into play. Now if I have followed Mr. Lamb rightly, his paper throws much light on my difficulty. Since the strength and persistence of the southern westerlies is clearly related to the geographical conditions of the southern hemisphere, it is logical to infer through the chain of factors described by Mr. Lamb, that the width of the equatorial rain-belt is also related to geographical conditions, and would be different if the Earth had a different geography. At all events it would appear that Mr. Lamb is on the right lines and would do well to pursue this interesting problem.

Mr. Miles : I have recently examined the connexion between the strength of the westerly circulation and the incidence of ' blocking ' between 20°W and 30°E in the northern hemisphere. For daily values of the circulation I have used the *Driftzahlen* published by Deutscher Wetterdienst,

Hamburg, and the dates of onset of blocking were taken from data made available by Mr. E. J. Sumner, Meteorological Office Dunstable and covering a period of eight years from 1949.

This examination shows that while in winter (Dec., Jan., Feb.) ' blocks ' are more often than not preceded by a peak of westerly circulation (within 8 days), this is clearly not so for those occurring in the spring (Mar., April, May), the time of maximum frequency of ' blocks.'

The late winter-early spring maximum of southern hemisphere ' blocking ' mentioned by Mr. Lamb may arise from occurrences of the former sort, but the overall scarcity of blocking may be due to an almost complete absence of the second kind.

Monthly mean charts of 500 mb topography for the northern hemisphere show a marked decrease in the westerly circulation from January through March to May, and not only in the sectors where ' blocking ' is most common. This suggests that the majority of ' blocks ' in this hemisphere arise from a slowing down of the circulation which appears to have no parallel in the southern hemisphere.

This slowing down can be largely attributed to a strong warming of the troposphere during the spring in the polar regions. The much smaller warming in the Antarctic region during the southern spring thus appears as one of the essential differences between the two hemispheres.

Prof. P. A. Sheppard (*President*) : Mr. Lamb deals in the main with mean motion in the southern hemisphere and shows that the zonal component of this is generally stronger than in the northern hemisphere. But it would be equally interesting to know how the kinetic energy compared in the two hemispheres and for this one needs an estimate of eddy energy as well as of energy of mean motion. Does Mr. Lamb have evidence on this ?

The comparison of kinetic energy would be particularly interesting because of the much larger meridional gradient of temperature in the southern hemisphere. From one point of view, that of hydrodynamic instability, one might expect the larger meridional temperature gradient (larger vertical wind shear) to result in larger eddy energy. However, the larger meridional gradient of temperature might be a reflection of lower eddy energy and a corresponding diminution of meridional heat transfer, so a good deal seems to hang on a comparison of kinetic energies.

One might also hope to gain insight into mechanisms of the general circulation by comparing the latitude of transition from surface easterlies to surface westerlies in the two hemispheres. Mr. Lamb's Fig. 3 shows a quite small difference only in latitude of transition for the winter seasons which suggests that this transition is not sensitive to variation of parameters. It would be interesting to hear his views.

Prof. Gordon Manley : I am greatly impressed with the world scale of Mr. Lamb's work and would wish to congratulate him. I noticed the very great change in the ratio between the net westerly angular momentum in the northern and southern hemispheres, between the southern autumn and the southern winter. That the overweight is most marked below 500 mb would point to the effect of the thermal gradient provided by the air overlying the antarctic ice-sheet. Does he find that this very rapid autumn-winter change tends to be concentrated in the month of May ? If that were so it would suggest that the mobility or stagnation of the surface air overlying the antarctic, which would be reflected in the mean temperature of May on the ice-sheet, might possibly be correlated to a significant extent with subsequent events in the north. Recently it has been suggested that attention might be paid to the locus of development of negative temperature anomalies in November in the Arctic. Although in some ways this might savour of old-fashioned climatology and correlation-hunts, in the light of Mr. Lamb's findings and the much greater size of the antarctic ice-sheet it looks as if any unusual late-autumn development of cold in that area might have widespread effects on a scale worthy of study.

Mr. H. H. Lamb (*in reply*) : In presenting the paper, I mentioned the following points where I thought it possible to throw further light since the paper was written :

(1) The Indian Ocean trough was usually the biggest, but was probably not the most ' anchored ' trough – in the sense of being tied to quite a narrow range of preferred longitudes. The troughs in the lower latitudes east of the Andes and east of New Zealand were probably more rigidly controlled as regards longitudinal position. In the case of the Indian Ocean trough, there are indications (*cf.* Loewe *et al.*, 1952) that the most frequent position lay farther west during the 1850's than it does today.

(2) In the light of seismic investigations of ice thickness during the I.G.Y., it appears probable that the lesser height of the west Antarctica ice dome, as compared with the great dome in east Antarctica, may be attributed to the fact that the bedrock under fairly considerable parts of west Antarctica is up to 2,500 m below sea level.

I agree with Professor Fleagle that the question of whether the greater energy of the southern circulation is more to be attributed to lesser friction than to greater thermal contrasts

remains unresolved. Geography determines that there is less friction in the zone of the southern than northern westerlies; but also the southern hemisphere with its polar continent, surrounding ocean and remaining landmasses in suitable latitudes for strong heating is about as favourably arranged as it could be for developing a strong latitudinal thermal gradient. The central pressures of the southern depressions are generally lower than those of the northern hemisphere, and the southern systems are probably more intense in terms of departure from the average pressure of the zone in which they occur, especially in summer. In summer the southern depressions are certainly the more intense and this must of course be attributable to the southern hemisphere's markedly stronger summer thermal gradient in middle latitudes. The southern-hemisphere depressions are also generally larger than their northern counterparts.

In reply to the related question put by Professor Sheppard, I have not investigated the distribution of energy as between the mean circulation and the individual systems. The energy of the mean southern circulation appears to exceed that of the northern, both in the zonal and meridional flows; prevalence of transgressions of the southern circulation across the equator presumably indicates greater energy, including greater eddy energy, in the south.

The latitude of changeover from a westerly to an easterly circulation in the subtropical belt appears to me to be related, through the position of the principal atmospheric thermal gradient and of the mainstream of the westerlies, to the latitude of the ice limit – most clearly in the case of the southern hemisphere where the ice limit approximates to a circle about the centre of the cold region.

In answer to Mr. Bonacina, I do not think that the position of the zenith sun at noon is very directly related to the position or development of the equatorial rain-belt. I believe the position, breadth and intensity of the intertropical convergence appears as a resultant of the respective drives from the southern and northern hemisphere circulations operating through the trade winds and the intensity and position of the subtropical anticyclones, whose development is in turn related to the circumpolar westerlies.

My allusion to the ' flywheel ' effect of the southern circumpolar westerlies was meant to refer chiefly to the ocean currents set in motion by the subtropical anticyclones. The chain of reasoning suggests that the supply of heat to the Gulf Stream (via the South Equatorial Current and the Caribbean Current) should be affected by variations in the strength or latitudinal position of the southern westerlies. Moreover, we now have evidence from independent work on secular changes that this is so. It seems safe to presume that the ocean circulation in the South Pacific is also affected by the southern westerlies; through the linkages with the Indian Ocean and the North Pacific this touches upon two of Sir Gilbert Walker's ' oscillations.' Inasmuch as these ocean effects involve a lag, it seems proper to liken the process to the way in which a flywheel operates.

I agree with Mr. Miles that the frequent ' blocking ' over the N. Atlantic in May is associated with a seasonal slowing down of the circulation, but I think it also depends upon the peculiar narrow shape of the residual cold trough over eastern Canada in spring – in other words it depends upon geographical features (geographical distribution of heating) which have no parallel in the southern hemisphere.

In answer to Professor Manley, I believe that the big change in the ratios of southern to northern hemisphere circulation intensity from northern winter to summer is primarily due to the big seasonal change in the northern hemisphere. The seasonal change in the southern hemisphere is much less impressive. This is a question of the summer heating of the northern temperate zone with its great continents. However, I strongly favour the idea that the locus of negative temperature anomalies developing not just in November, but from the very beginning of the northern autumn, is important for the subsequent winter development. This may be all the clearer because winter is the season when the northern circulation should be most nearly independent of influences from the contemporary southern circulation. Presumably, the most significant factors are the early development in one sector or another of excessive sea-ice and snow-cover on land, either of which tends to react upon the atmospheric circulation in such a way as to favour its own maintenance. It is possible that autumn development of excessive sea-ice in one sector or another round the Antarctic (from March to May onwards) has similarly important inertia and lag effects: this is a point for study, but the possibilities of break-up of the ice may be significantly greater in the Antarctic.

Reference

Loewe, F., Radok, U. and Grant, A. 1952 *Berichte des dt. Wetterdienst. U.S. Zone*, Bad Kissingen, **7**, 42, pp. 11-15.

Report of the Council

for the year 1958

Submitted to the Annual General Meeting, 22 April 1959

General

The Council are glad to report that a good measure of progress has been achieved in the past year. The Society's activities have covered a wide range and, in spite of a small decrease during the year, the membership remains above 2,000, a number which was first exceeded in 1953.

Steps taken by the preceding Council and approved by the Fellowship to increase the membership fees with effect from 1 January 1958 are reflected in the Statement of Income and Expenditure. At the same time the subscription rates to the *Quarterly Journal* were also raised and this measure has also led to an increase in income.

The fifth two-day Summer Meeting was held at Dublin. Further details are given later in the Report.

Three vacation courses were successfully held in conjunction with the Field Studies Council : one mainly for those interested in flying, at Preston Montford; one for sixth-formers, also held at Preston Montford, with the main emphasis on Field Studies; and a third for sixth-formers and undergraduates held at Malham Tarn.

Council

From 1 January to 30 September the constitution of the Council was as recorded in the 1957 Annual Report.

From 1 October 1958 the following Council held office :

President

Professor Percival Albert Sheppard, Hon. A.R.C.S., B.Sc., F.Inst.P.

Vice-Presidents

Alan West Brewer, Ph.D.
Howard Latimer Penman, M.Sc., Ph.D., F.Inst.P.
Charles Henry Brian Priestley, M.A., Sc.D., F.Inst.P.
Reginald Cockcroft Sutcliffe, O.B.E., Ph.D., F.R.S.

Vice-President for Canada

Robert Campbell Graham, B.A.

Vice-President for Scotland

James Robert Atkinson, M.A.

Treasurer

Brian Cecil Vernon Oddie, B.Sc.

Secretaries

Patrick John Meade, O.B.E., B.Sc.
Richard Segar Scorer, M.A., Ph.D.
John Stanley Sawyer, M.A., (Editor)
Arthur George Forsdyke, Ph.D., A.R.C.S. (Librarian)

Councillors

George Arthur Corby, B.Sc.
Instr. Capt. Charles Roy Darlington, B.Sc., R.N.
Thomas Herbert Ellison, M.A., Ph.D.
Frank Henry Winn Green, M.Sc.
Robert Frederick Jones, B.A.
Basil John Mason, D.Sc.
Robert James Murgatroyd, Ph.D.
Edward Thomas Pierce, Ph.D.
Reginald Charles Rainey, Ph.D.
John Brodrick Rigg, M.A.
Charles Desmond Walshaw, M.A., Ph.D.
Henry Lionel Wright, M.A.

The Council met nine times during the year and there were thirty-two Committee Meetings.

Meetings

Eight Ordinary Meetings and two Special General Meetings were held in the Society's rooms during the year and a Joint Meeting with the National Society for Clean Air was held at Agriculture House, London S.W.1, when papers on ' Progress in atmospheric pollution research,' ' The introduction of smoke control areas,' ' Climatological aspects of air pollution ' and ' Radio activity in the atmosphere ' were read.

Council also introduced as an experimental measure a series of Evening Discourses with the object of inviting recognized authorities to give general surveys of particular branches of meteorology. The first of the series was given in November when Dr. B. J. Mason spoke on ' Recent developments in the physics of rain and rain-making.'

Three vacation courses were successfully held in conjunction with the Field Studies Council, two at Preston Montford and one at Malham Tarn. Of the Preston Montford courses one catered mainly for those who were interested in meteorology from the aviation aspect, while the other was largely concerned with the applications of meteorology to general field studies.

Dr. E. T. Pierce gave the Society's Popular Lecture on ' Thunderstorms ' at County Hall, Westminster, on two successive evenings on 20 and 21 November.

The Annual General Meeting was held in the Society's rooms on 23 April when the Report of Council and the Annual Accounts for 1957 were adopted. The Presidential Address was given by Professor P. A. Sheppard, his subject being ' Transfer across the earth's surface and through the air above.'

The Symons Memorial Lecture was given on 2 April by Professor C. W. Allen, Professor of Astronomy in the University of London, his subject being ' Solar radiation.'

The Summer Visit on 9 July was to the Rothamsted Experimental Station, Harpenden, Herts., by kind invitation of the Director, Sir William Ogg. Some seventy members and guests took part and spent a most interesting day. Council expressed to Sir William Ogg and also to Dr. H. L. Penman, who, as Head of the Physics Department of the Station, was responsible for the excellent arrangements, their appreciation of an altogether most interesting visit.

Summer Meeting, Dublin, 25-27 July 1958

The fifth two-day Summer Meeting of the Society was held at Dublin by kind invitation of the Department of Meteorology and Geophysics, School of Cosmic Physics, Dublin, and took place in the Museum Buildings, Trinity College, by permission of the Provost. The Meeting opened on the evening of 25 June with a reception given by the Provost of Trinity College, Dublin.

Two symposia were held. The President, Professor P. A. Sheppard, was in the Chair at the first symposium on 'Atmospheric aerosols.' Papers were read by Professor L. W. Pollak on 'Photo-electric nucleus counter and its applications,' Prof. P. J. Nolan on 'The calibration of the photo-electric nucleus counter,' Mr. G. J. Day on 'The distribution of Aitken nuclei in the free atmosphere,' Dr. K. H. Stewart on 'Some optical measurements in fogs and their interpretation' and Mr. W. G. Durbin on 'Daily aircraft sampling of condensation, freezing and chloride nuclei in January 1958.'

Prof. L. W. Pollak took the Chair at the second symposium, which began with a discussion on 'Aeronautical meteorology,' opened by Mr. J. W. O'Byrne on 'Meteorological service for transatlantic flights' and Mr. P. K. Rohan followed with 'Some aspects of aviation-route weather over the North Atlantic.'

The second half of the morning's discussion was opened by Mr. E. Knighting on 'The movement of depressions,' followed by Mr. R. P. W. Lewis on 'Jet streams.'

An exhibition of work by early Irish meteorologists was on view in the Library of Trinity College during the meeting.

Social events included a visit on Thursday to the Guinness Brewery preceded by luncheon by kind invitation of the Managing Director, Mr. C. K. Mills, to whom thanks were expressed by the President.

Visits were also made to Prof. Pollak's Department in the School of Cosmic Physics, and to the Meteorological Office at Dublin Airport at the invitation of Dr. M. Doporto, Director of the Irish Meteorological Service.

On Friday afternoon there was an enjoyable excursion by coach to Glendalough and Avoca and in the evening a reception was held by the President of University College, Dublin.

The Council record their thanks to Mr. R. F. Jones, who acted as co-ordinator, and to Prof. Pollak and his colleagues on the local Committee who contributed so much to the success of the meeting.

Publications

The inflow of scientific communications for the *Quarterly Journal* was slightly down on 1957 although it was somewhat greater than in 1956. 62 papers were submitted for publication during 1958 as against 64 in 1957 and 58 in 1956. Papers published during the year numbered 44. The average time between receipt of approved copy and publication in the *Journal* was about $4\frac{1}{2}$ months. The four numbers of the 1958 *Journal* together contained 493 pages as compared with 572 in 1957.

Council are greatly indebted to the Editor, Dr. G. D. Robinson, (and later to Mr. J. S. Sawyer), the Editing Committee and the proof reader, Mr. E. L. Hawke, for their services in the production of the *Journal*.

The Society's monthly magazine, *Weather*, continued to maintain a high standard of production and of technical content and Council are greatly indebted to the *Weather* Editing Committee for their valuable work. Much lively correspondence, interesting editorials and several controversial articles have been published. Council wish to remind the Membership that *Weather* provides a suitable medium for the publication of papers of a somewhat less specialized nature than those which appear in the *Quarterly Journal*. Since *Weather* enjoys a wide readership among meteorologists everywhere, it can be confidently recommended to authors.

Membership

Table A

	Fellows and Foreign Members			Associates	Students	Honorary Members	Total
	Annual	Life	Total				
31 Dec. 1957	1,430	175	1,605	33	105	12	1,755
Since elected	94	1	95		24		119
Re-admitted	6		6				6
Transferred	7	2	9	1	— 15	5	—
Deceased	— 10	— 5	— 15			— 1	— 16
Resigned	— 78		— 78	— 2	— 10		— 90
Struck off	— 42		— 42	— 1	— 3		— 46
31 Dec. 1958	1,407	173	1,580	31	101	16	1,728
Canadian Branch							
31 Dec. 1957	66	5	71	270			341
31 Dec. 1958	77	5	82	256			338
Grand Total							
31 Dec. 1957	1,496	180	1,676	303	105	12	2,096
31 Dec. 1958	1,484	178	1,662	287	101	16	2,066

Deaths

The Council record with sorrow the deaths of Captain C. Adams, Life Fellow 1940, elected in 1913; Dr. A. J. Bamford, Councillor, elected to Fellowship in 1912; Prof. C. F. Brooks, Life Foreign Member, elected in 1920; Dr. J. S. Farquharson, Honorary Treasurer of the Society and Life Fellow since 1934; Sir Alexander Gibb, elected Life Fellow of the Scottish Meteorological Society in 1912, transferred to Fellowship of the Royal Meteorological Society 1921; Sir Ernest Maclagan Wedderburn, elected to the Scottish Meteorological Society in 1908, Honorary Secretary of the Scottish Meteorological Society 1908, Scottish Chairman and Vice-President 1949 to 1952; Henryk Arctowski, Foreign Member (1933); Eric Harvest (1956); Vera Huckle (1957); I. T. Nelson, Fellow of the Scottish Meteorological Society (1913); F. Tattersall, Fellow (1949); O. P. T. Turner, Fellow (1944); Sir Gilbert Walker, elected to Fellowship 1905, President 1926-27, Symons Gold Medallist 1934, Honorary Member 1952.

Library

Loans personally and by post have been maintained but the increased postal charges are apparently proving a deterrent to the use of the Library. There was a slight increase in the number of inquiries dealt with.

Thirteen new series of journals and memoirs have been received. All were included within existing arrangements for an exchange or were supplied free.

A further selection of the older books and journals in bad repair has been rebound.

The lantern-slide collection has been overhauled. A catalogue for the revised collection is in course of preparation.

' Master ' whole-plate prints of selected negatives in the Clarke collection of cloud photographs have been made and arrangements are in hand for similar action with selected negatives in the Cave collection. Arrangements have also been made for storage of the selected negatives of both collections.

Staff

During the year Mr. M. E. Shoenberg tendered his resignation as Assistant Secretary. In recognition of Mr. Shoenberg's valuable work for more than nine years, Council unanimously agreed upon his election to Honorary Life Fellowship.

The Officers took steps to fill the vacancy, and, after considering a large number of applicants recommended to Council the appointment of Mr. R. H. Levinson, M.A., A.C.A., who accordingly commenced his duties on 29 September 1958.

Other members of the staff consisted of Mr. R. S. Read, I.S.O., M.A., B.Sc., A.R.C.S., F.Inst.P., Assistant Librarian; Mrs. A. Wallis, Accounting Assistant; Mrs. W. A. Steward, Editorial Assistant and Publications Clerk; Miss D. E. Hall, Secretarial Assistant; Miss E. Crafts, *Weather* Clerk and Miss E. Hooper, Junior Clerk.

The Officers and Council have pleasure in recording their high appreciation of the work of the staff during the past year.

Branch and Centres

Canadian Branch

Eight meetings were held in Toronto during the year, in addition to the Annual General Meeting in January. The meetings on 4 November and 6 November were the Fifth National meetings, and were attended by members from all parts of Canada.

The Committee consisted of President, Dr. W. L. Godson; Vice-President, Dr. R. H. Douglas; Vice-President for Canada, Mr. R. C. Graham; Treasurer, Mr. R. L. Titus; Corresponding Secretary, Mr. P. I. Johns; Recording Secretary, Mr. R. R. Dodds; Councillors-at-Large, Chairman of the Montreal Centre, Chairman of the Winnipeg Centre, LCDR. M. G. Hagglund, Dr. F. K. Hare, Mr. D. B. Kennedy, M.B.E., Mr. J. R. Lauder.

Montreal Centre. Six meetings were held in the Faculty Club of McGill University during 1958, with average attendance exceeding thirty. In addition, on 13 December, members were the guests of the McGill University Chemistry Society to hear Dr. Bernard Vonnegat speak on 'Electrical phenomena in the atmosphere released by thunderstorms.' The Officers were: Chairman, Mr. J. L. Galloway; Secretary, Dr. Svenn Orvig; Treasurer, Mr. D. E. McClellan.

Winnipeg Centre. Five meetings were held in 1958 with the average attendance approximately twenty. A programme of presentation of meteorological texts and publications to Winnipeg libraries was initiated. The Officers were: Honorary Chairman, Mr. S. V. A. Gordon; Chairman, Mr. A. B. Lowe; Vice-Chairman, Mr. L. C. Oddy; Secretary-Treasurer, Mr. P. Kowal.

Scottish Centre

Four meetings were held during the year at Edinburgh University and an excursion was made in May to Eskdalemuir Observatory. In March, Mr. H. H. Lamb delivered his popular Lecture for sixth-form pupils on 'Weather in the polar regions.'

The Committee consisted of: Chairman and Vice-President for Scotland, Mr. J. R. Atkinson; Secretary and Treasurer, Mr. D. H. McIntosh; and eleven other Fellows.

Manchester Centre

The centre had a Membership of about twenty-four, most of whom being very regular in their attendance at meetings. Six meetings were held during the year and in each case an address was delivered.

Two Popular Lectures to sixth-form pupils were given in conjunction with the Manchester Education Committee. In March Mr. H. H. Lamb gave an address to about 300 pupils on 'Polar meteorology' and in November Dr. E. T. Pierce lectured on 'Thunderstorms' to 130 senior boys and girls.

In April the Centre mounted a display of instruments and photographs at an exhibition on the topic of 'Heat' organized by the Manchester Federation of Scientific Societies.

The Committee consisted of: Chairman, Professor P. R. Crowe; Secretary, Mr. N. K. Horrocks; Treasurer and Assistant Secretary, Dr. H. P. Palmer; and nine other Fellows.

Representatives

The Society's representatives on other scientific bodies were:

Royal Society Committees

Gassiot Committee, President; *British National Committee for Geodesy and Geophysics*, R. C. Sutcliffe (1958-1963), T. W. Wormell (1955-60); *British National Committee for Physics*, F. Pasquill (1955-60).

Institute of Physics Advisory Committees
Journal of Scientific Instruments, H. L. Penman; *British Journal of Applied Physics*, G. D. Robinson.

Cambridge University Meteorological Committee
Professor P. A. Sheppard.

Royal Astronomical Society, Geophysical Committee
G. D. Robinson.

Advisory Committee on Meteorology for Scotland
Sir Charles Normand.

British Glaciological Society
Professor Gordon Manley.

Awards

The following awards were presented at the Annual General Meeting on 23 April :

Buchan Prize, in respect of the period 1953-1957

Richard Mead Goody, M.A., Ph.D., for his outstanding contributions to the theory and observations of the absorption and emission of radiation in the atmosphere as given in the following two papers in the *Quarterly Journal* :

' Equations of transfer for the total flux of terrestrial radiation,' **79**, p. 282, 1953.
' A simple grating spectrometer for sky-emission studies,' **83**, p. 517, 1957.

And in collaboration in the following papers :

' The origin of atmospheric nitrous oxide ' by R. M. Goody and C. D. Walshaw, *Q.J.*, **79**, p. 496, 1953.

' An investigation of the 9·6 micron band of ozone in the telluric spectrum ' by R. M. Goody and C. D. Walshaw, *Proceedings Toronto Meteorological Conference 1953*, p. 27.

' Absorption by the 9·6 micron band of ozone ' by C. D. Walshaw and R. M. Goody, *Proceedings Toronto Meteorological Conference 1953*, p. 49.

' Spectral line shape and its effect on atmospheric transmissions ' by A. R. Curtis and R. M. Goody, *Q.J.*, **80**, p. 58, 1954.

' An experimental investigation of the 9·6 micron band of ozone in the solar spectrum ' by C. D. Walshaw and R. M. Goody, *Q.J.*, **82**, p. 177, 1956.

' Determination of the vertical distribution of ozone from emission spectra ' by R. M. Goody and W. T. Roach, *Q.J.*, **82**, p. 217, 1956.

Hugh Robert Mill Medal and Prize for 1957

Leo Claude Wallace Bonacina, a friend and colleague of H. R. Mill, whose interest in precipitation in Britain has covered a period of more than fifty years. His formal contributions, mainly to *British Rainfall*, are concerned with the exposure of raingauges and with the distribution of snowfall, but it is by informal means, during his long association with the Royal Geographical Society as well as with the Royal Meteorological Society that he has made his influence most felt. His contributions to discussion, both public and private, must have stimulated the thoughts of many with better opportunity for quantitative investigation, and his obvious love of the British scene and countryside secured the co-operation of many others to the cause of precipitation measurements.

Darton Prizes for 1957

Home Awards :
1st Prize : Mr. J. W. Hutchings.
2nd Prize : Mr. I. F. Long.

Canadian Awards :
1st Prize : Dr. T. W. R. East.
2nd Prize : Mr. J. Clodman.

Scientific Activities Fund

During the year the following grants were made :

Mr. F. M. Bushby and Dr. G. B. Tucker for travelling expenses in attending the two-day Summer Meeting at Dublin.

Mr. P. M. A. Bourke towards travelling expenses incurred in the study of potato blight.

Prof. T. V. Davies towards cost of attending an Applied Mechanics Congress at Opatija, Abbazia, Yugoslavia.

Prof. H. Égner to cover expenses in travelling from Sweden to take part in a discussion meeting on ' Atmospheric chemistry.'

Finance

There is a surplus of £919 for the year, as compared with a surplus of £99 in 1957 and a deficit of £253 in 1956. The improvement in the Society's financial position is, of course, the result of the increased subscriptions introduced last year. The accounts make it clear that the increases were necessary, for without them, there would have been a deficit of about £1,500.

The Society's policy, introduced in 1957, of investing about half its capital in industrial stocks, is yielding satisfactory results. The value of the Society's industrial holdings on 31 December was £9,785, representing an appreciation of about 9 per cent since they were bought. The Society's gilt-edged holdings now valued at £10,979, have on the other hand declined in value by about 2 per cent in the last two years.

Members who have a professional interest in meteorology are now permitted to treat their subscriptions to the Society as a business expense for income tax purposes. This should provide a valuable stimulus to new membership, for its effect is that, for those subject to United Kingdom income tax, the cost of Fellowship may be less than £2 10s. per annum. It is thought that some Fellows will wish to transfer the benefit of the new regulations to the Society by an appropriate donation.

Council have taken advantage of the easier financial position to carry out some necessary redecoration of the Society's premises, especially of the stairway leading to the maisonettes. Changes in the Rent Restriction Act have enabled the Society to increase substantially its income from the maisonettes.

In general, the financial position of the Society continues to be satisfactory. The rise in subscriptions a year ago led to a number of resignations but, as shown earlier in this Report, the loss of membership was not very serious, and there is good reason to hope that it will be recovered in the present year.

RECEIPTS AND PAYMENTS OF SPECIAL FUNDS FOR 1958

	Balance at 31.12.57	Income for 1958	Expenditure for 1958	Balance at 31.12.58
	£	£	£	£
Awards Fund	10	—	4	6
British Rainfall Organization Fund	72	2,208 (a)	2,281 (b)	1 Dr.
Life Composition Fund	60	232	201 (c)	91
Napier Shaw Memorial Fund	192	67	—	259
Royal Society Reprints Scheme	16	3	5	14
Scientific Activities Fund	87	167 (d)	187	67
Staff Pension Fund	705	609 (e)	778 (f)	536
Symons Memorial Fund	29	31	16	44
Hampton Brown Fund	14	59	43	30
	£1,185	£3,376	£3,515	£1,046

(a) Includes £2,036, proceeds of 62 Camden Square; (b) Includes £376, cost of transfer to new premises and £1,690 for £2,000 4% Australia 1966/68 Stock; (c) Includes £200 transferred to " A " account; (d) Includes £100 grant from " A " account; (e) Includes transfer of 15% of Salaries £450; (f) Payment of calls on £150 6% B.P. Deb. Stock £118. Purchase of 300 Beecham Group Ltd. 5/– Ordinary £294. Purchase of 375 Distillers Co. Ltd. 10/– Ordinary £365.

Examined and found correct
1 April 1959

BALL, BAKER & CO.,
Chartered Accountants

VALUATION OF INVESTMENTS AT 31 DECEMBER 1958

Market Value 31.12.57			*Market Value 31.12.58*	
£	£		£	£
		*General Fund**		
869		£1,250 4% Consols x.d.	912	
173		£200 4% Funding Stock 1960/90	181	
526		£649.1.7 Government of Commonwealth of Australia 4% Registered Stock 1955/70	555	
1,670		£2,000 4% Government of Commonwealth of Australia 4% Registered Stock 1966/68 x.d.	—	
356		£100 Burmah Oil Co. Ltd. Ordinary Stock	400	
519		£287 Guest Keen & Nettlefold Ltd. Ordinary Stock	832	
213		£200 Courtaulds Ltd. Ordinary Stock	345	
420		200 Marks & Spencer Ltd. "A" Ordinary 5/- Shares	555	
—		£160 Babcock & Wilcox Ltd. Ordinary Stock	410	
—		£250 Vickers Ltd. Ordinary Stock	450	
—		£131 Unilever Ltd. Ordinary Stock	576	
—		£130 John Dickinson & Company Ltd. Ordinary Stock	512	
—		£150 Tube Investments Ltd. Ordinary Stock	628	
4,746				6,356
		Scientific Activities Fund		
158		£250 3½% War Stock 1952 or after	166	
63		£100 3½% Conversion Loan 1961 or after	66	
765		£1,000 4% Trinidad Government Stock 1973/76	800	
986				1,032
		Staff Pensions Fund		
626		£900 4% Consolidated Stock 1957 or after x.d.	657	
383		£500 4% Trinidad Government Stock 1973/76	400	
429		£600 3½% Treasury Stock 1979/81	465	
445		£500 Bowater Paper Corporation Ltd. 5¼% Convertible Unsecured Loan Stock 1978/82	522	
475		£200 English Electric Co. Ltd. Ordinary Stock	612	
413		£150 Turner & Newall Ltd. Ordinary Stock	574	
38		£150 British Petroleum Co. Ltd. 6% Convertible Debenture Stock 1976/80 (£20 paid 31.12.57)	162	
—		375 Distillers Company Ltd. Ordinary 10/- Shares	503	
—		300 Beecham Group Ltd. Ordinary 5/- Shares	386	
2,809				4,281
		Life Composition Fund		
243		£350 4% Consolidated Stock 1957 or after x.d.	255	
715		£1,000 3½% Treasury Stock 1979/81	775	
445		£500 Bowater Paper Corporation Ltd. 5¼% Convertible Unsecured Loan Stock 1978/82	522	
383		£300 Imperial Chemical Industries Ltd. Ordinary Stock	570	
243		£100 Canadian Eagle Oil Company Ltd. Ordinary Shares n.p.v.	279	
2,029				2,401
		*British Rainfall Organization Fund***		
473		£750 3½% War Stock 1952 or after	499	
1,889		£3,097.10.0 British Transport 3% Guaranteed Stock 1978/88	2,060	
70		£100 4% Consolidated Stock 1957 or after x.d.	73	
215		£300 3½% Treasury Stock 1979/81	222	
—		£2,000 4% Government of Commonwealth of Australia Registered Stock 1966/68 x.d.	1,790	
2,647				4,644
		Napier Shaw Memorial Fund		
221		£350 3½% Conversion Loan 1961 or after	233	
278		£400 4% Consolidated Stock 1957 or after x.d.	292	
499				525
		Symons Memorial Fund		
410		£650 3½% Conversion Loan 1961 or after	432	
139		£200 4% Consolidated Stock 1957 or after x.d.	146	
549				578
		Hampton Brown Fund		
769		500 Hawker Siddeley Group Ltd. Ordinary £1 Shares	800	
86		250 Marley Tile (Holding) Co. Ltd. "A" Ordinary 5/- shares	147	
855				947
£15,120				£20,764

* General Fund also includes the Freehold of 49 Cromwell Road, S.W.7.

** British Rainfall Organization Fund included the Freehold of 62 Camden Square, N.W.1 at 31.12.57. This has since been sold and the part of the proceeds invested in £2,000 4% Government of Commonwealth of Australia Registered Stock 1966/68.

Examined and securities seen
1 April 1959

BALL BAKER & CO.,
Chartered Accountants

GENERAL

BALANCE SHEET AT

31-12-57							
£	£	£		£	£	£	
			ACCUMULATED FUND—				
	12,401		Excess of Assets over Liabilities at 1st January 1958		12,111		
	463		*Deduct* Library Equipment Fund		619		
	11,938				11,492		
	389		*Deduct* Loss on Sale of Investments		340		
	11,549				11,152		
	99		*Add* Excess of Income over Expenditure		919		
11,648							12,077
463			LIBRARY EQUIPMENT FUND				619
—			REPAIRS RESERVE FUND				356
			CURRENT LIABILITIES—				
	944		Creditors and Accrued Charges		1,238		
			Amounts Received in Advance :				
		1,427	Publications	1,289			
		426	Subscriptions	329			
	1,853				1,618		
2,797							2,856

P. A. SHEPPARD—*President*

B. C. V. ODDIE—*Treasurer*

We have examined the above Balance Sheet and annexed Income and Expenditure Account which in our opinion respectively give a true and fair view of the state of the Society's affairs as at 31 December 1958, and of its income and expenditure for the year ended on that date.

Spencer House,
South Palace,
LONDON, E.C.2.
1 April 1959.

BALL, BAKER & Co.,
Chartered Accountants

£14,908	£15,896

FUND

31 DECEMBER 1958

31-12-57 £	£		£	£
		FIXED ASSETS—		
5,375		Freehold Property – Estimated value (in 1925) of the Society's House, 49 Cromwell Road		5,375
		Furniture and Equipment—		

		At 1-1-58	Additions during year	Accumulated Depreciation	Net	
1,108	General	1,536	163	556	1,143	
463	Library	606	218	205	619	
1,571		£2,142	£381	£761	£1,762	1,762

(No amount has been included for the value of the Library and the stock of publications)

	INVESTMENTS—		
	Valued at Market Price 31.12.54 with additions since at cost—		
1,206	£1,250 4% Consolidated Stock 1957 or after ..	1,206	
206	£200 4% Funding Stock 1960/90	206	
645	£649.1.7 Government of Australia 4% Registered Stock 1955/70	645	
2,030	£2,000 Government of Australia 4% Registered Stock 1966/68	—	
562	£100 Burmah Oil Co. Ltd. Ordinary Stock ..	562	
612	£287 Guest, Keen & Nettlefolds Ltd. Ordinary Stock	612	
368	£200 Courtaulds Ltd. Ordinary Stock	368	
506	200 Marks & Spencer Ltd. "A" Ordinary 5/- Shares	506	
—	£160 Babcock & Wilcox Ltd. Ordinary Stock ..	396	
—	£250 Vickers Ltd. Ordinary Stock	392	
—	£131 Unilever Ltd. Ordinary Stock	392	
—	£130 John Dickinson & Co. Ltd. Ordinary Stock	414	
—	£150 Tube Investments Ordinary Stock	425	
6,135			6,124
	(Market Value 31.12.58 £6,356)		
	(Market Value 31.12.57 £4,746)		

	CURRENT ASSETS—				
383	Stock of Stationery				495
	Debtors—				
£	*Proceedings Toronto Meteorological Conference*	£			
43	*1953*	8			
291	Subscriptions	527			
963	Publications	815			
1,297		1,350			
150	*Less* Provision for Bad and Doubtful Debts ..	250			
1,147			1,100		
58	Payments in advance		25		
26	Deposit at Post Office and Cash in Hand ..		50		
213	Balance at Bankers		965		
1,444					2,140
£14,908					£15,896

EXPENDITURE

1957 £	£	£		£	£	£
			ESTABLISHMENT—			
	25		Water Rates		26	
	283		Cleaning Wages and Materials		275	
	22		Insurance		24	
	183		Lighting and Heating		248	
	145		Repairs and Maintenance		271	
	115		Depreciation of Furniture and Equipment		127	
773						971
			ADMINISTRATION—			
		Weather		*Weather*		
	2,745	388	Salaries	432	3,028	
	408		Contribution to Staff Pension Fund		450	
	39		Printing		122	
	308	107	Stationery	90	284	
	304	423	Postage, Carriage and Packing	629	374	
	82		Telephone		87	
			Audit and Accountancy Fees—			
	105		Royal Meteorological Society		105	
	31		*Weather* Magazine	31		
			Legal Expenses		14	
	45	7	Sundries	13	64	
4,992						5,723
			PUBLICATIONS, ETC.—			
	3,978		*Quarterly Journal*		3,948	
	2,382		*Weather*		2,394	
	327		Illustrations		284	
	155		*Cloud Study*		132	
	98		Reprints of *Weather*		103	
	255		Reprints of Papers		214	
	37		*Monthly Weather Report*		34	
			Members' copies of *Weather* contra. against *Weather* Sales £1,150 (31.12.57 £985)			
	61		Second-hand Journals		24	
7,293						7,133
			LIBRARY—			
	486		Salary		491	
	162		Books, Bindings, etc.		210	
	46		Depreciation of Equipment		62	
694						763
			MEETINGS' EXPENSES—			
	201		Travelling Expenses		67	
			London		105	
	40		Scotland		40	
	30		Manchester		30	
	33		Weather Meetings		20	
304						262
37			PROVISION FOR BAD AND DOUBTFUL DEBTS—			128
			GRANTS AND PRIZES—			
	100		Scientific Activities Fund		100	
	40		Grant to Society for Promotion of Field Studies		40	
140						140
—			Transfer to Repairs Reserve Fund			350
99			BALANCE, BEING EXCESS OF INCOME OVER EXPENDITURE			919
£14,332						£16,389

FUND

FOR THE YEAR ENDING 31 DECEMBER 1958

INCOME

1957 £	£	£		£	£	£
			SUBSCRIPTIONS, ETC.			
	5,418		Subscriptions		7,160	
	105		Entrance Fees		96	
	22		Donations		18	
	5,545				7,274	
	110		*Less*: Adjustments for Lapsed Membership (By-law 40)		145	
5,435						7,129
			PUBLICATIONS—			
	3,067		Sale of Publications – current *Q.J.*		3,856	
	1,122		Sale of Publications – back numbers *Q.J.*		750	
	1,571		Sale of *Weather* – excluding members' copies		1,476	
	190		Sale of *Cloud Study*		294	
	300		Reprints		267	
	108		Reprints of *Weather*		113	
	525		Advertisements		525	
	952		Advertisements – *Weather*		915	
	15		*Proceedings Toronto Meteorological Conference 1953*— Sales etc.		8	
	12		Sundry Sales		24	
7,862						8,228
			INVESTMENT INCOME—			
	215		Interest on Government Stocks (Gross)		191	
	27		Interest on Industrial Securities (Gross)		100	
		282	Rent of Maisonettes	210		
		127	*Less*: Rates	—		
	155				210	
397						501
			PHOTOGRAPHS—			
	17		Sale of Cloud Postcards		8	
		91	Clarke and Cave Copyright Fees	142		
		—	*Less*: *Reproduction Costs*	44		
	91				98	
108						106
			LIBRARY—			
300			Grant from the Royal Society			200
			AMOUNTS RECEIVED FROM OTHER FUNDS—			
	200		Life Composition Fund		200	
	30		British Rainfall Organization Fund (for Administration)		15	
230						215
—			Profit on Sale of Typewriter			10
£14,332						£16,389

Proceedings at meetings of the Society

Ordinary Meeting, 18 March 1959

The following candidates were declared to have been elected that day by the Council : :

Fellows

Bate, Peter Maxwell, Officers Mess, R.A.F. (Staging Post), Katunayake, Ceylon (*transfer from Student Membership*).
Spiller, Henry Anthony, B.Sc., 7 Cleveland Place East, Bath, Somerset.
Wood, Capt. William Harry Brittain, c/o Malayan Airways, Paya Lebar Airport, Singapore.

Foreign Members

Feeley, John Francis, B.Sc., Weather Bureau Airport Station, Air Mail Field, Buffalo, New York, U.S.A.
Manabe, Syukuro, Ph.D., General Circulation Research Section, U.S. Weather Bureau, Federal Office Building $\neq\neq$ 4, Suitland, Maryland, U.S.A.
Ruff, Irwin Stanley, B.S., M.S., 150 West End Avenue, Brooklyn 35, New York, U.S.A.
Williams, Roger Terry, 560 North 5th Street, Covina, California, U.S.A.

Canadian Branch

Fellow

Truhlar, Edward James John, M.A., c/o Department of Transport, Goose Bay, Labrador, Newfoundland.

The following papers were read and discussed :

1. ' The southern westerlies : a preliminary survey; main characteristics and apparent associations ' by H. H. Lamb (*Q.J.*, **85**, p. 1).
2. ' Absorption and emission in the atmospheric window from 770 to 1,250 cm^{-1} ' by W. T. Roach and R. M. Goody (*Q.J.* **84**, p. 319), presented by Dr. W. T. Roach.

Symons Memorial Lecture, 1 April 1959

Mr. J. A. Ratcliffe, F.R.S., Reader in Physics in the University of Cambridge and Fellow of Sydney Sussex College, delivered the Symons Memorial Lecture, his subject being ' The highest parts of the ionosphere.'

Annual General Meeting, 22 April 1959

Professor P. A. Sheppard, Hon. A.R.C.S., B.Sc., F.Inst.P., in the Chair. The minutes of the Annual General Meeting held on 23 April 1958 were confirmed and signed.

The President in presenting the Report of the Council for 1958 referred to the main items of interest.

The effects of the increase in subscription for membership and the *Quarterly Journal* were reflected satisfactorily in the year's accounts, in spite of a slight decline in total membership.

The Society had had a successful year of considerable activity. The meetings during the year included a Joint Meeting with the National Society for Clean Air which was held at Agriculture House, London, S.W.1.

As an experimental measure, a series of Evening Discourses was initiated with the object of having specialists who would survey particular branches of meteorology. The first of the series was delivered in November by Dr. B. J. Mason, who spoke on ' Recent developments in the physics of rain and rain-making.'

In co-operation with the Field Studies Council courses had been held at Preston Montford and Malham Tarn.

The summer visit to the Rothamsted Experimental Station was held by the kind invitation of the Director, Sir William Ogg. The fifth two-day Summer Meeting was held at Dublin in the Museum Buildings, Trinity College, by the kind permission of the Provost. Our thanks were due to Professor L. W. Pollak for the success of the meeting and to Mr. R. F. Jones, who acted as co-ordinator.

The high standard of the *Quarterly Journal* had been maintained and the special thanks of the Council were recorded to the Editor, Dr. G. D. Robinson (and later Mr. J. S. Sawyer), the Editing Committee and Mr. E. L. Hawke, the Society's proof reader.

Weather, the Society's monthly magazine, continued to maintain a high standard and Council recorded its appreciation to the *Weather* Editing Committee for their valuable work.

The President made special mention of the Library and urged Members to avail themselves more fully of the services it renders.

The Treasurer in reviewing the financial results of 1958 pointed out that, for the first time, the accounts of *Weather* were incorporated with those of the Society, so that comparison with the previous year's statement was not possible.

Special reference was made by the Treasurer to the benefits derived from the Society's policy introduced in 1957 of investing half its capital in equity stocks.

The Inland Revenue had now agreed to allow Members' subscriptions as a charge against income for tax purposes.

This year's surplus was £919, which was satisfactory, and as a result of the easing of the Society's financial position, part of the Society's House had been redecorated. A Repairs Reserve Fund had been instituted against which the cost of major redecoration could be charged.

The President moved that the Report be received and adopted and that it be printed in the *Quarterly Journal*. The motion was carried unanimously.

Mr. F. H. Ludlam proposed a vote of thanks to the President and the Council for their work during 1958, and this was seconded by Dr. G. B. Tucker.

The President then announced the following awards :

(a) *Symons Memorial Gold Medal for 1959.*

To Sir Graham Sutton, C.B.E., F.R.S., Director-General of the Meteorological Office, London, for his outstanding work in the field of micrometeorology.

(b) *Darton Prize for 1958.*

Home Awards : (1) Mr. R. J. Taylor for his paper ' A linear unidirectional anemometer of rapid response ' (*J. Sci. Inst.*, **35**, p. 47, 1958). (2) Mr. D. D. Clark for his paper ' A thermometer for high-speed aircraft.' (*J. Sci. Inst.*, **35**, p. 433, 1958).

Canadian Awards : (1) Mr. J. L. Galloway for his papers ' The three-front model : its philosophy, nature, construction and use ' and ' The three-front model, the tropopause and the jet stream ' (*Weather*, Jan. 1958, Dec. 1958). (2) Mr. R. W. Longley for his paper ' Temperature variations at Resolute, Northwest Territories ' (*Q.J.* **84**, p. 459, 1958).

Professor P. A. Sheppard, Hon.A.R.C.S., B.Sc., F.Inst.P., then delivered the Presidential Address, his subject being ' Education and research in meteorology in the United Kingdom.' Mr. H. L. Wright proposed a vote of thanks to the President for his Address and asked that he would allow it to be printed in the *Quarterly Journal*. Mr. J. B. Rigg seconded the vote of thanks. The meeting was declared closed at 7.15 p.m.

Ordinary Meeting, 13 May 1959

The Meeting took the form of a Discussion starting at 2.30 p.m. on ' The dynamics of cumulonimbus.' As Opening Speaker, Dr. R. S. Scorer spoke on ' The thermal theory of atmospheric convection.' Mr. P. M. Saunders then presented Miss Betsy Woodward's paper on ' The motion in and around isolated thermals ' (*Q.J.*, **85**, p. 144). This was followed by a discussion on ' Convection without fall-out.'

After the tea interval, the President presented the Symons Memorial Gold Medal for 1959 to Sir Graham Sutton, C.B.E., F.R.S., Director-General of the Meteorological Office, London, for his outstanding work in the field of micrometeorology, and read the following citation :

> Sir Graham Sutton has over many years contributed with remarkable originality to the theory of atmospheric diffusion and of evaporation and he has done much to create an ordered body of knowledge in the field of micrometeorology, to which his text ' Micrometeorology ' bears effective witness. His work has been distinguished by a happy combination of physical intuition and mathematical development whereby he has provided results of great interest and lasting utility to pure and applied meteorology. He has greatly stimulated those with whom he has laboured and his gift of clear exposition has been appreciated by all who know his works.

After the reply to this award, by Sir Graham Sutton, the President announced the name of the winner of the Napier Shaw Memorial Prize for 1959 as being Professor S. K. Runcorn for his essay : ' Climatic change through geological time in the light of the palaeomagnetic evidence for polar wandering and continental drift.' The adjudicators had also accorded honourable mention to Mr. H. H. Lamb and Mr. A. I. Johnson for their joint essay ' Climatic variation and observed changes in the general circulation.'

Mr. F. H. Ludlam continued the Discussion Meeting with a talk on ' Hail growth and cumulonimbus evolution,' followed by Mr. W. G. Harper on ' Radar studies of the movement of mature thunderstorms.' Mr. E. H. Boyenval showed a film of Doppler radar, and the meeting closed with a general discussion on ' Raining cumulus.'

At the conclusion of the Ordinary Meeting the President and Council were joint hosts with the Chairman and Directors of Messrs. Decca Radar Ltd. at a reception in the Society's rooms to welcome visiting meteorologists from the Commonwealth.

THE NAPIER SHAW MEMORIAL PRIZE

Second Award of the Napier Shaw Memorial Prize

March 1954 was the centenary of the birth of Sir Napier Shaw, first Director of the Meteorological Office, first Professor of Meteorology at Imperial College, President of the International Meteorological Organization, and President of this Society.

A fund was established by the Society to commemorate his unique position in meteorology and it was decided to award a prize of £100 at intervals of not more than three years for an original essay on a set subject.

The second competition was announced in July 1956 (*Q.J.*, **82**, p. 383), the subject being ' Climatic variation,' and was closed on 1 January 1959.

The adjudicators in April 1959 recommended the award of the Napier Shaw Memorial Prize for 1959 to Professor S. K. Runcorn of the Department of Physics, Newcastle (University of Durham), for his essay ' Climatic change through geological time in the light of the palaeomagnetic evidence for polar wandering and continental drift ' and this was announced by the President at the Ordinary Meeting of the Society on 13 May 1959.

The adjudicators accorded honourable mention to Mr. H. H. Lamb and Mr. A. I. Johnson for their joint essay ' Climatic variation and observed changes in the general circulation ' which contains original work likely to afford considerable stimulus to the development of the subject.

Reviews

Descriptive meteorology. By H. C. Willett and F. Sanders. London (Academic Press), 2nd Edition, 1959. Pp. xix, 355; 70 Figs. $7.50.

This is the second edition of a book which was published by Professor Willett in 1944. The changes that have been made are mostly those resulting from advances in meteorological knowledge. In writing an introductory text for students who may have no more than an elementary knowledge of mathematics and physics the authors have put the emphasis on ' organisation and continuity of presentation,' with no attempt at completeness in scope. In achieving coherence and maintaining the theme of the book they have been highly successful, and incidentally the reader is spared the usual tedious chapters on how to make and plot observations.

The evolution of the subject is logical and purposeful. The introductory chapters describe the composition of the atmosphere and explain the importance of vertical stability. Chapter 3 deals with the heat balance, and applies the principles in discussing the observed global distribution of surface and upper-air temperature. This more basic part of the book then concludes with evaporation and condensation and the fundamental mechanics of airflow.

Most of the second half of the book deals with circulation on various scales. First, there is a chapter on the general circulation. Then come ' secondary circulations ' of thermal origin, such as monsoons and hurricanes. The next chapter deals with secondary circulations of the dynamic type – the ordinary depressions and anticyclones – and finally there are what are called tertiary circulations, which are the small-scale systems produced thermally or mechanically. The final chapter, not a very rewarding one, is in the nature of an appendage; it is on weather forecasting and weather modification, which, we are told, are the practical objectives justifying the dollars spent on research.

When a book is written as an introduction to meteorology, it is difficult for a meteorologist to be certain how well that end is achieved. Firstly it must be said that the writing of *Descriptive meteorology* is fluent and that most of the reasoning is admirably clear. Its construction bears the mark of a good teacher, in that it anticipates the questions which arise in the mind of the assiduous reader. The title might imply too much statement of fact and too little concern with physical processes; on the contrary, every opportunity is taken to argue from cause to effect and from there to observational confirmation. A criticism is that the reasoning might have been more specific here and there, as in the explanation of vorticity, which could have been made more understandable by the introduction of mathematics of no higher standard than appears elsewhere. There is also a tendency to assume that the reader is acquainted with the nature of day-to-day weather developments; a selection of synoptic charts would have been helpful to the newcomer. Indeed the conscientious reader deserves more diagrams generally.

Most meteorologists will find this book makes profitable and interesting reading. The beginner in meteorology will almost certainly be given an appetite for more. Not everyone, therefore, will approve of the authors' policy of avoiding almost completely any reference to sources of information or to other books of a general nature. This is not, they say, a reference book. However, what it sets out to do is done very well indeed.

C.J.B.

Météorologie generale, Tome II. Stabilité verticale de l'atmosphère. Vent et turbulence atmosphérique. Nuages et precipitations. By J. Roulleau and R. Trochon. Paris (Gauthier-Villars), 1958. Pp. 178 : 84 Figs.; 77 Tables. 1700fr.

This book is the second volume of a series of monographs published under the direction of the Director of the French Meteorological Service. The first volume, published in 1952, dealt with the vertical structure of the atmosphere and radiation.

In this volume the opening chapters are concerned with the thermodynamics of dry and moist air, stability and vertical motion, the equations of motion and their application to the steady state. The fifth chapter deals with turbulence, applying the equation $\frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial z^2}$ to derive the diurnal variation of temperature at different levels, the logarithmic law of wind variation with height near the ground, and the variation illustrated by the Ekman spiral at higher levels ; nine pages of this chapter are devoted to the statistical treatment of turbulence using the Euler and Lagrange correlation coefficients. The last chapters describe the growth of condensation nuclei and the constitution and formation of cloud, fog and rain. Two photographs are reproduced illustrating the bright band seen on radar screens, and reference is made to successful experiments in rain-making by the French Meteorological Service.

The book contains much useful and up-to-date information with references to papers published up to 1955. The subjects are developed in a characteristically logical manner on a mathematical foundation. Students with advanced-level mathematics who can read French with ease should find the book worthy of study.

H.L.W.

Weather and climate. By C. E. Koeppe and G. C. De Long. New York (McGraw-Hill), 1958. Pp. viii, 341 : 3 Colour Maps; 85 Figs.; 88 Plates; 18 Tables. 58s.

The palpable controls exercised by weather and climate on human, economic and social rhythms are aspects which are central to the interests of geography. An understanding of weather conditions both on the ground and aloft, and of world climates, is thus of real concern to the geographer. Regrettably not all

geographers have the necessary background in mathematics and physics to follow a standard course in technical meteorology and few are equipped to undertake primary research in this science. It is for such geographers that this book has been written. It attempts to present an up-to-to-date, reasonably complete and scientifically accurate treatment of weather and climate without recourse to mathematics and physics beyond the simplest concepts. The latter obviously imposes a limitation on the authors – two American geographers – and the resulting volume is thus elementary and introductory. Nevertheless, much scientific information is successfully imparted whilst retaining the interest of the non-scientist reader.

The first half of the book is concerned with a discussion of the weather principles and processes, including the nature, extent and composition of the atmosphere; the weather elements, their measurement and variations (horizontally and vertically) daily, seasonally and annually; the general circulation of the atmosphere, including jet streams; air masses and fronts; and the American weather map and weather forecasting. Many of the eleven chapters in this section differ from their counterparts in other textbooks only in viewpoint and organization.

In the second half of the book, climate is first presented as a study of general principles and later as descriptive climatology in which emphasis is placed upon genesis and upon geographical position. Acknowledging the geographer's genuine interest in climate as a factor in the environment, the description of the climatic types is based on the quantitative classification of Köppen. This treatment may well offend the British temperament, which is generally averse to the classification of natural complexes, but failure to classify is to ignore real necessities imposed by progress in research and by the elaboration of established knowledge. Köppen's classification attempts to give climatic limits of characteristic soil and vegetation regions but is of limited use in a study of climate as a factor influencing human distributions directly through physiological effects. Despite the useful contributions of Griffith Taylor and Sir David Brunt the direct effects of climate on man's health and comfort have yet to be reduced to a set of simple parameters and incorporated in a comprehensive classification.

This pleasing volume is abundantly illustrated with maps, diagrams, half-tone illustrations and three-coloured plates – ' Natural vegetation of the world ' (Küchler); ' ' Climates of the world ' (Köppen-Geiger); ' Climatic regions of the world ' (Koeppe). It should prove a useful textbook for sixth-form and first-year college students of geography, and for the non-scientist general reader anxious to sample meteorology and climatology without the possibility of becoming discouraged through lack of an adequate technical background.

G.M.H.

Klimatographie von Österreich. Bd. 3, Pt. I. Eds. F. Steinhauser, O. Eckel, F. Lauscher. Vienna (Springer-Verlag), 1958. Pp. 136; 26 Figs.; 88 Tables; 4 Folding maps. 51s.

The publication under review is the first part of a new climatology of Austria which is being edited by Prof. F. Steinhauser, Dr. O. Eckel and Prof. F. Lauscher (respectively Director, Vice-Director and Head of Climatology in the Central Institute for Meteorology and Geodynamics) and published by the Vienna Academy of Science.

The Part opens with an account by Dr. F. Hader of the topography of Austria accompanied by a $1 : 10^6$ map to set the scene for the subsequent climatology with its marked orographic variations. Next there come 90 pages on the radiation climate by Dr. F. Sauberer and Dr. I. Dirmhirn. This deals with direct solar radiation, sky and global short-wave radiation, long-wave radiation, radiation balances, daylight illumination and ultra-violet radiation. The effects of cloud, topography, and industrial pollution are considered in detail under each heading. There is a fair network of stations measuring solar radiation but the daylight illumination observations are restricted to Vienna and ultra-violet observations to Davos in Switzerland. Finally we have 46 pages on sunshine by Dr. F. Steinhauser. The observational network is, of course, large for this element and its variations with season and in space are treated in great detail, with four seasonal maps of the distribution of the percentage of possible sunshine across the country. These maps show that while mountains receive roughly twice as much sunshine as plains in winter, in summer the plains receive rather more than the mountains.

The publication is well produced with excellent figures. No information is given as to the contents of future Parts. This new publication following the recent detailed account of the climatology and climatic history of Vienna bids fair to make the climatology of Austria the best described in the world.

G.A.B.

The weather-conditioned house. By G. Conklin. New York (Reinhold), 1958. Pp. xiv, 238 : 234 Figs.; 75 Tables. 118s.

Throughout the world a great deal of effort is being devoted to studies of the way a building reacts with the weather. It is a two-way relationship, for not only does the weather affect buildings in a multitude of ways, but the buildings themselves affect the weather (or at least the climate) in their vicinity. In a considerable assemblage of buildings the reaction makes a significant change in the local climate.

While many architects and engineers are aware of these facts, and that climate is not the same over the whole globe, others seem to be ignorant in this matter. This would appear to be proved by the current ' international ' style of architecture, which is to be found in almost every country – a style which largely ignores climate and climatic difierences. Usually the native styles of building take account of local climate, but only too often these indigenous examples have been ignored.

The author of *The weather-conditioned house* has attempted to describe the ways in which the internal climate of a building can be controlled by use of suitable materials and constructional devices, and by heating or cooling plant. He also deals with deterioration factors, acoustics and fire control, of which the latter are rather outside the scope of the title.

Much of the text and tabular matter seems to come from standard works on the subject and may be assumed to be accurate. It is, however, painfully clear from parts of the text which are the author's own that he has little understanding of the basic theory. In Chapter 3 on 'Principles of thermal comfort,' for example, it is obvious that he does not appreciate the difference between thermal conductivity and thermal conductance, while his explanations of humidity concepts are confused or inaccurate. In consequence, although the author mentions the important factors to be considered in climatic control of buildings, a reader attempting to follow some of the 'theoretical' explanations in this book would become hopelessly confused. It is perhaps unfortunate that the 'Publishers' note' on the dustcover mentions that among the author's works are some on 'fantasy and science fiction.' One may legitimately ask why publishers of such distinction should decide to produce this book. Is it that the genuine specialists in this field have not the time available to write the books that are still needed?

R.E.L.

The magneto-ionic theory and its applications to the ionosphere. By J. A. Ratcliffe. Cambridge (University Press), 1959. Pp. xi, 206; 74 Figs.; 2 Tables. 40s.

Magneto-ionic theory is the study of the propagation of radio waves in the ionosphere, as influenced by the earth's magnetic field. Ratcliffe's book is a handbook giving the theory of this propagation, in a form suitable for an experimenter working on the subject.

The core of the book is its second chapter, in which are derived the basic equations for the (complex) refractive indices and polarization of the characteristic waves. The rest of the book includes three chapters in which subsidiary points of the derivation are discussed from a microscopic standpoint; six chapters on the interpretation of the equations, in the main graphically; three chapters on the application of the equations to model ionospheres; and finally, four chapters on possible modifications of the equations (the Lorentz term, the influence of heavy ions, the effects of inhomogeneities, and a comparison with anisotropic dielectrics). Essentially the later chapters are simply a development and illustration of the equations derived in the second chapter.

The book is concerned with these equations rather than with the morphology and reflecting properties of the actual ionosphere, which are regarded as likely to be known by the reader. Properties of model ionospheres are considered in detail, but where problems of the actual ionosphere are discussed (e.g. the Luxembourg effect, or triple splitting of the $h'(f)$ traces), they are discussed as applications of the basic equations, and not in their own right. The author enjoys letting himself go over one or two of the ionospheric topics, but they are, none the less, subsidiary to the main development.

Equally, the author does not go deeply into the fundamental theory underlying the propagation. The arguments of chapter 3 (on the dispersion equation) and chapter 5 (on absorption) are virtually a re-statement, in a longer form, of an argument essentially the same as that of chapter 2. When really difficult theoretical problems arise, e.g., as regards the Lorentz term, Ratcliffe contents himself with a reference to the original papers.

I am a little sorry that the book tends to keep off both the properties of the actual ionosphere and the more fundamental aspects of theory. However, its primary concern is with the actual propagation of waves. One's primary recommendation of it is therefore to people themselves concerned in studying this propagation.

T.G.C.

Physics of meteor flight in the atmosphere. By E. J. Opik. *Interscience tracts on physics and astronomy.* No. 6. Ed. by R. E. Marshak. London, (Interscience Publishers), 1958. Pp. viii, 174; 14 Figs.; 55 Tables. $1.95.

The physical processes which occur during the flight of a meteor into the earth's atmosphere have been studied in some detail during the last few decades, particularly since the last war. They include considerations of the physico-chemical properties of meteors, the way energy is transferred to them as they enter the earth's atmosphere, their ablation and the ionization and radiation produced. From these studies and visual or radar observations of the appearance, brightness and deceleration of the meteors and the drift of their trails it has been possible to obtain considerable data on the temperature, density and winds in the upper atmosphere, mainly between 60 and 120 km above the earth's surface. Hence this subject is of great interest to meteorologists. The scope of this booklet, however, is limited to the basic physics and it does not deal with methods of observation or meteorological results. Indeed the author, stating that our knowledge of meteors is much less certain than that of the atmosphere, inverts the meteorological problem and uses a standard atmosphere to infer the properties of meteors which are compatible with the observations. The purely meteorological content is therefore small and the book can only be recommended to meteorologists as background reading. It is, however, a very interesting introduction to the astronomer's problems and a useful, if in places somewhat controversial, statement of the present state of knowledge of this subject.

R.J.M.

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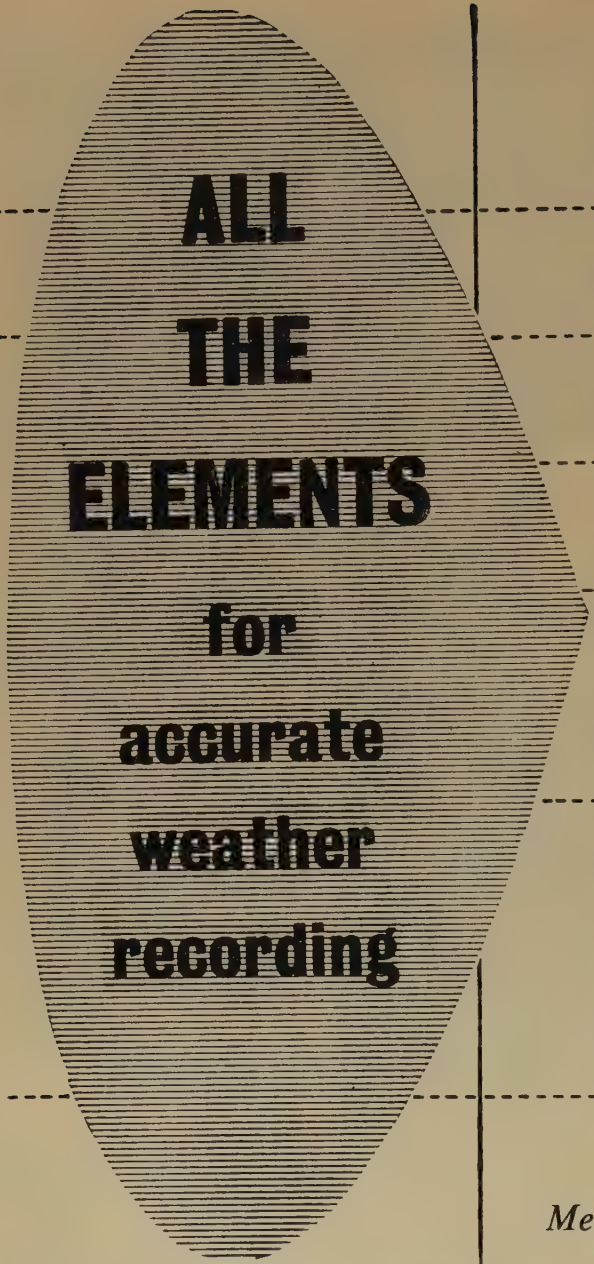

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Published by John Murray

Foreword by R. C. SUTCLIFFE, O.B.E., Ph.D., F.R.S.
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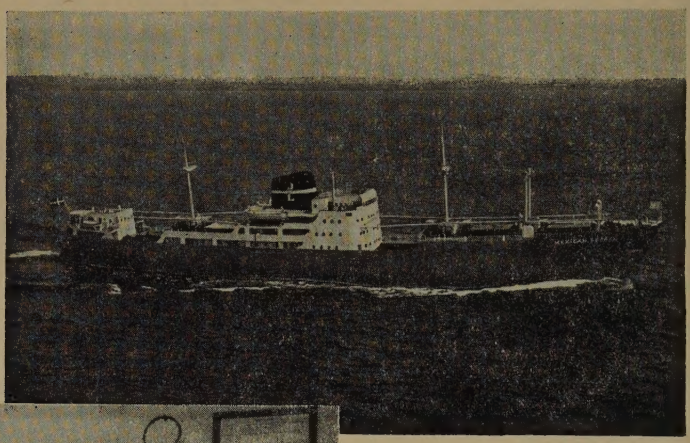

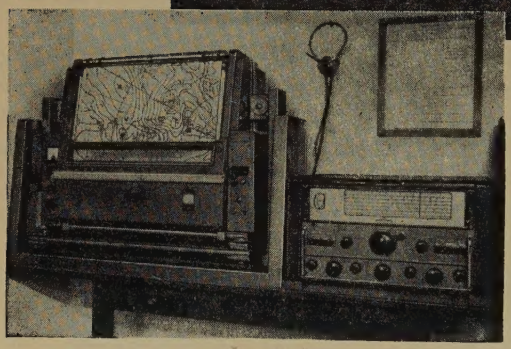

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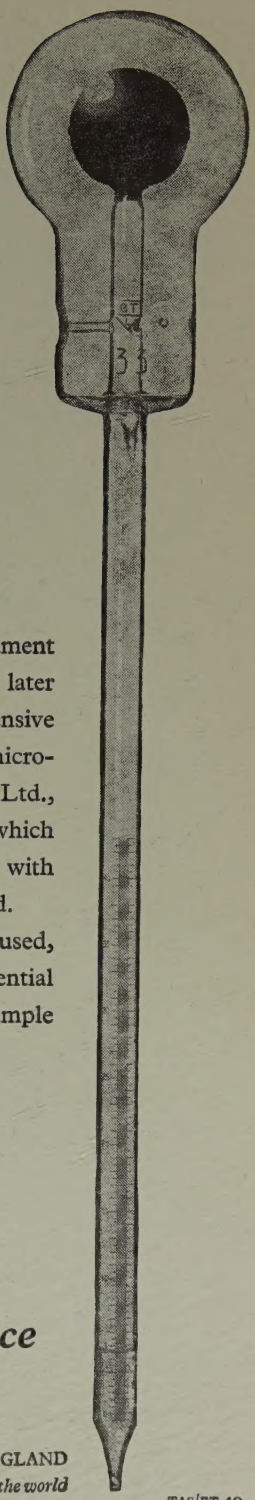

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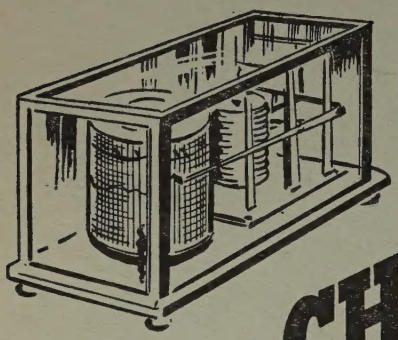

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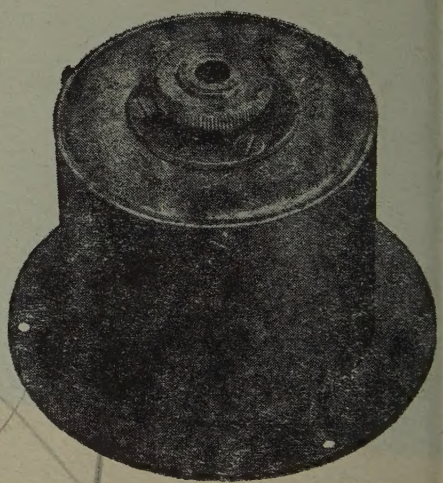

Horstmann Chart Clocks are used extensively by the Air Ministry Meteorological Office. Two types are available, one to drive chart drums revolving once in every 24 hours and the other for 7 day rotation. The clockwork movements of both types have a centre spindle drive.

The movements are of robust construction and incorporate very high quality jewelled platform escapements, which ensure extreme accuracy in time keeping.

Chart Clocks having speeds other than those mentioned above can also be supplied to special order.

THE HORSTMANN GEAR CO. LTD. · NEWBRIDGE WORKS · BATH · Tel.: Bath 7241

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